Refinements to the stratigraphic nomenclature of the Santa Fe Group, northwestern Albuquerque Basin, New Mexico

Sean D. Connell

New Mexico Geology, v. 30, n. 1 pp. 14-35, Print ISSN: 0196-948X, Online ISSN: 2837-6420.
https://doi.org/10.58799/NMG-v30n1.14

This page is intentionally left blank to maintain order of facing pages.

Refinements to the stratigraphic nomenclature of the Santa Fe Group, northwestern Albuquerque Basin, New Mexico

Sean D. Connell, New Mexico Bureau of Geology and Mineral Resources, Albuquerque Office,
New Mexico Institute of Mining and Technology, 2808 Central Ave. SE, Albuquerque, New Mexico 87106, connell@gis.nmt.edu

Abstract

Recent geologic mapping refines the stratigraphic nomenclature of the Santa Fe Group in the Albuquerque Basin of the Rio Grande rift of central New Mexico. Discovery of an unconformity requires modifications to the stratigraphic nomenclature of the Santa Fe Group in the western Albuquerque Basin. The Rincones paleosurface represents a tectonostratigraphic boundary that separates slightly tilted, upper Miocene sediments of the Arroyo Ojito Formation from overlying, weakly consolidated, and subhorizontally stratified deposits of the Pliocene Ceja Formation. Correlation of the Rincones paleosurface constrains the distribution of component depositional belts across much of the basin and resolves a long-standing problem with stratigraphic correlations within the Albuquerque Basin.

Revisions to the Santa Fe Group stratigraphic nomenclature in the northwestern Albuquerque Basin are intended to aid in future geologic mapping activities and in the interpretation of geologic compilations of the Albuquerque Basin. Use of the term "middle red formation" (or member) should be discontinued because it is ambiguously defined. The following revisions are proposed: raise the Cerro Conejo Member of the Zia Formation to formation rank; propose the Picuda Peak Member for the upper part of the Arroyo Ojito Formation; elevate the Ceja Member of the Arroyo Ojito Formation to formation rank and locally divide it into the Atrisco, Santa Ana Mesa, and Rio Puerco Members. The Pantadeleon Formation has similar composition to, and occupies the same stratigraphic position as, the Ceja Formation and should be abandoned as redundant to the senior term Ceja Formation.

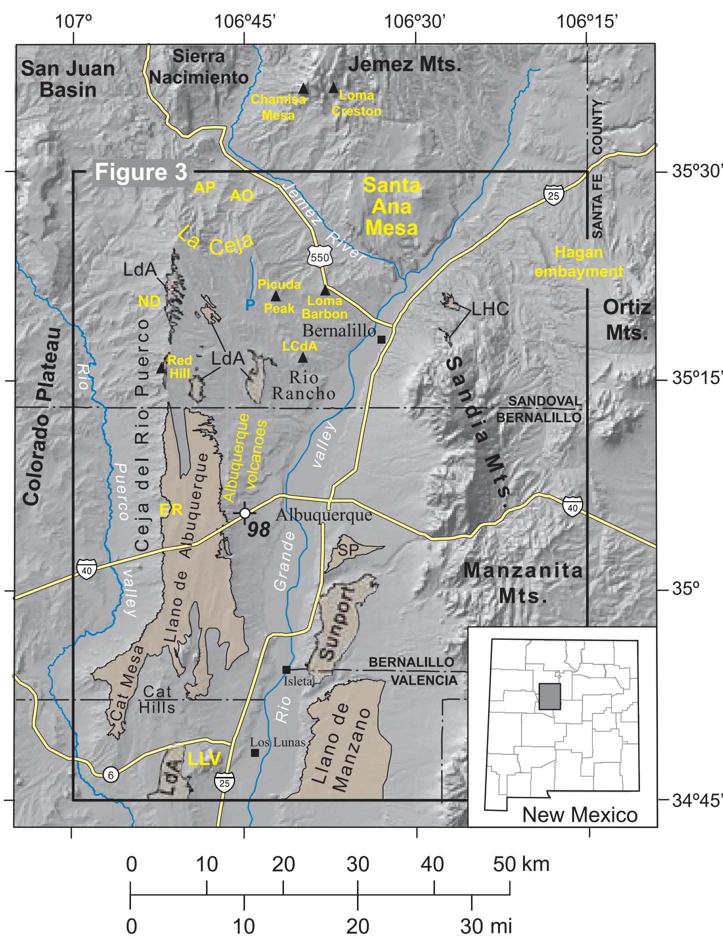


FIGURE 1—Study area location in the northwestern Albuquerque Basin, illustrating major highways, outline of simplified geologic map (Fig. 3), key physiographic features, and geomorphic surfaces discussed in this paper. The Llano de Albuquerque (**LdA**), Llano de Manzano, Sunport (**SP**), and Las Huertas (**LHC**) geomorphic surfaces represent local constructional tops of the Santa Fe Group. Other features include the Zia stratotype at Arroyo Piedra Parada (**AP**), the Cerro Conejo and Arroyo Ojito stratotypes at Arroyo Ojito (**AO**), the Atrisco type drill hole at 98th Street (**98**), and the Ceja stratotype at El Rincón (**ER**). Other locations include Arroyo Pantadeleon (**P**), Cat Hills, Ceja del Rio Puerco, Chamisa Mesa, Loma Barbon, Loma Colorado de Abajo (**LCdA**), Loma Creston, Los Lunas volcano (**LLV**), Navajo Draw (**ND**), Picuda Peak, and Red Hill.

Introduction

The Albuquerque Basin of central New Mexico (Fig. 1) was subjected to intensive geologic and geophysical investigations that began during the early 1990s. The treatment of the stratigraphy of the Albuquerque Basin varied among different maps (e.g., Connell 1998 2006; Koning et al. 1998; Koning and Personius 2002; Maldonado et al. 2007; Personius 2002; Personius et al. 2000; Shroba et al. 2003; Williams and Cole 2005, 2007). A factor contributing to the lack of consensus in stratigraphic nomenclature was that a regionally consistent lithostratigraphic framework for the Albuquerque Basin had not been developed at the time. Later recognition of key stratigraphic relationships resolved some of these ambiguities. Periodic refinements to the stratigraphic nomenclature of geologic basins are a logical and expected result of continued mapping and the evolution of stratigraphic concepts. This paper proposes refinements to the stratigraphic nomenclature of Miocene and Pliocene deposits in the northwestern Albuquerque Basin (Fig. 2G). These refinements are intended to aid in stratigraphic correlations within and among basins of the Rio Grande rift in New Mexico and to aid in the interpretation of geologic compilations of the Albuquerque Basin (Table 1), including those of Williams and Cole (2005, 2007), Connell (2006, in press), and Maldonado et al. (2007).

Where appropriate, regional stratigraphic terms were adopted from previous investigations. The Rincones paleosurface refers to an unconformity between Pliocene and upper Miocene deposits that was first reported by Connell and Smith (2005). Deposits assigned to the "middle red" by various authors are recognized above and below the Rincones paleosurface in the Albuquerque Basin (Fig. 2A, F, and G). Use of the term "middle red formation" (or member; Bryan and McCann 1937; Kelley 1977; Williams and Cole 2005) should be discontinued because it is ambiguously

TABLE 1—Comparison of map units used in this study and Connell (2006, in press), Williams and Cole (2005, 2007), and Maldonado et al. (2007). Unit Tcrp replaces Tcrg of Connell (2006). Unit Tcau refers to an upper sandy unit in the Atrisco Member (Connell 2006).

Name	Connell (2006, in press)	Williams & Cole (2005, 2007)	Maldonado et al. (2007)
Ceja Formation	Tc	Tc & QTu	Tc
Rio Puerco Member	Tcrp (Tcrg)	Tc	Tcu
Atrisco Member	Tca (Tcau)	Tmb	Tcm
Santa Ana Mesa Member	Tcs	Tm	—
Arroyo Ojito Formation	To	—	—
Picuda Peak Member	Top	Tc	—
Loma Barbon Member	Tob	Tm & Tmb	—
Navajo Draw Member	Ton	Tmn	Tcl
Cerro Conejo Formation	Tcc	Tmc	—

defined. Additional age constraints for the Navajo Draw and Loma Barbon Members are briefly described and are intended to supplement previous descriptions (i.e., Connell et al. 1998, 1999; Connell 2004). The Cerro Conejo lithostratigraphic unit is elevated to formation rank to settle conflicts regarding previous usage (see Connell 2004). The Picuda Peak Member of the Arroyo Ojito Formation is defined herein to resolve miscorrelations between the Ceja and Arroyo Ojito stratotypes (sensu Connell et al. 1999). The Pantadeleon Formation is abandoned because it has a similar composition and occupies the equivalent stratigraphic position as the Ceja Formation. The Ceja Formation is divided into the Atrisco, Santa Ana Mesa, and Rio Puerco Members.

Regional geologic setting and previous work

The Santa Fe Group is the sedimentary and volcanic fill of the Cenozoic Rio Grande rift (Chapin and Cather 1994). The Santa Fe Group is commonly divided informally into two or three sub-groups (e.g., Haw-

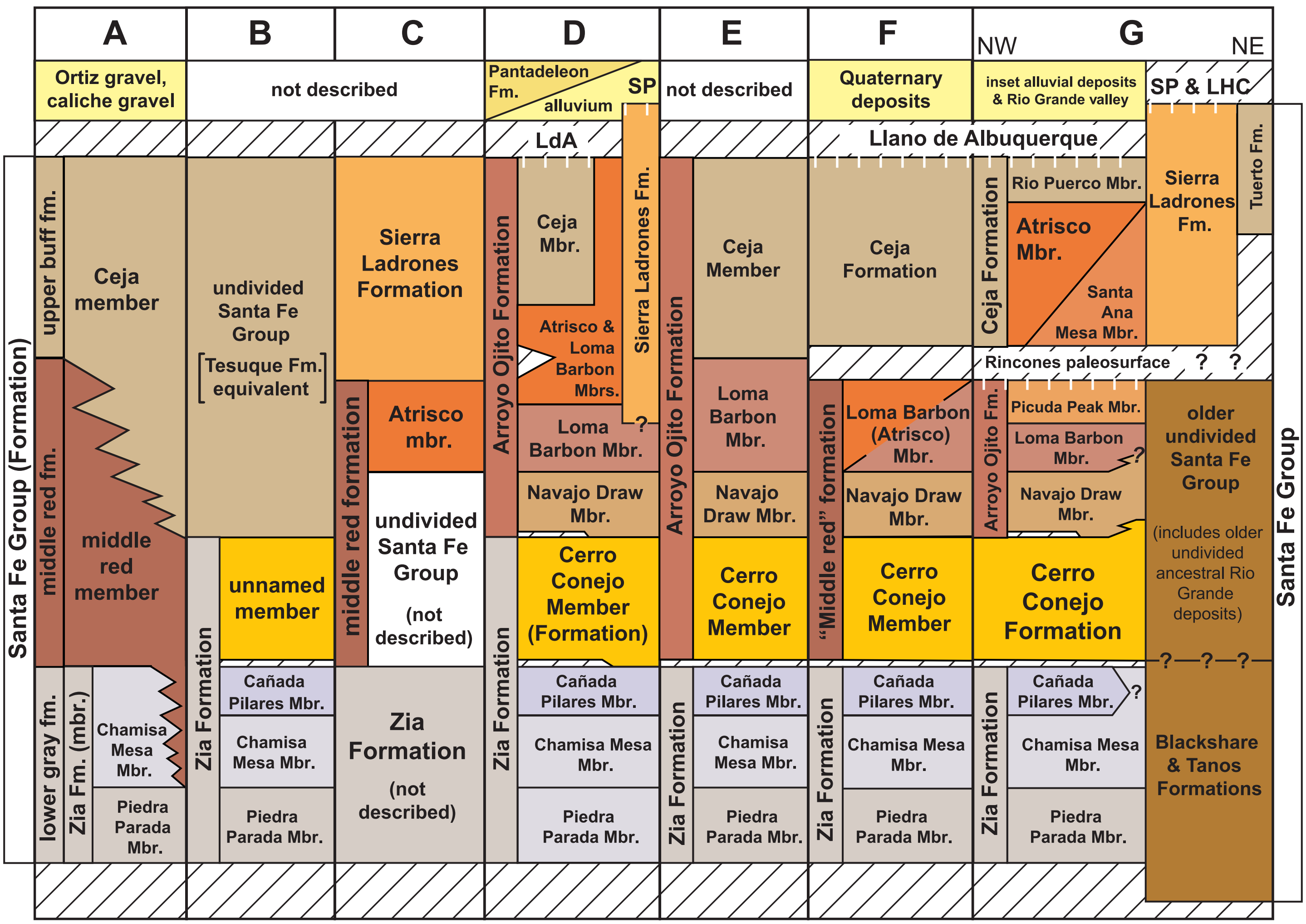


FIGURE 2—History of usage of stratigraphic nomenclature in the northwestern Albuquerque Basin. Black diagonal lines denote stratigraphic lacunae. White hachure denotes soils locally associated with geomorphic surfaces, including the Rincones paleosurface, Llano de Albuquerque (**LdA**), and Sunport (**SP**) and Las Huertas (**LHC**) geomorphic surfaces. **Column A**—compilation of studies by Bryan and McCann (1937), Wright (1946), Spiegel (1961), Galusha (1966), and Kelley (1977). **Column B**—Galusha and Blick (1971), Gawne (1981), Tedford and Barghoorn (1997), and Beckner and Mozley (1998). **Column C**—Atrisco member of Connell et al. (1998). **Column D**—Cerro Conejo Member (Zia Formation), Arroyo Ojito Formation, and Pantadeleon Formation definitions of Connell et al. (1999). Connell (2004) suggested placing the Atrisco Member in the Arroyo Ojito Formation, and raising the Cerro Conejo to formation rank. **Column E**—Tedford and Barghoorn (1999) included the Cerro Conejo in the Arroyo Ojito Formation. **Column F**—stratigraphic nomenclature for Albuquerque 30′ by 60′ quadrangle compiled by Williams and Cole (2005, 2007). **Column G**—stratigraphic nomenclature proposed in this study and used in compilation by Connell (2006, in press).

ley 1978; Chapin and Cather 1994; Connell 2004). The lower Santa Fe sub-Group is commonly interpreted to record deposition within internally drained basins, where streams derived from emerging basin-margin uplifts terminated onto broad alluvial plains or into ephemeral and intermittent playa lakes and alluvial flats (e.g., Chapin and Cather 1994). The upper Santa Fe sub-Group is commonly defined by the onset of through-going axial-fluvial drainage that linked previously isolated basins of the lower sub-group (e.g., Gile et al. 1981; Chapin and Cather 1994; Connell et al. 2005). A middle sub-group is locally defined for deposits that are transitional between lower and upper sub-groups (e.g., Hawley et al. 1995; Connell 2004; Connell et al. 2005).

Inset alluvium associated with younger stream valleys is excluded from the Santa Fe Group (Spiegel and Baldwin 1963, p. 39). This definition of the top of the Santa Fe Group is allostratigraphic in nature and has only partial lithologic basis because of compositional similarities between the underlying Santa Fe Group basin fill and deposits associated with the present valleys (see Connell 2004). The delineation of geomorphic and structural controls on the termination of widespread basin aggradation are further complicated by the timing of tributary drainage integration, influences of Pliocene–Pleistocene climate change on river discharge and sediment yield, and the influence of intrabasinal faults on sedimentation (Connell 2004; Connell et al. 2007a). Delineation of post-Santa Fe Group strata can be locally ambiguous; however, most workers agree that the end of Santa Fe Group deposition occurred when the ancestral Rio Grande and major tributaries began to incise into older basin fill (e.g., Gile et al. 1981; Chapin and Cather 1994; Mack et al. 2006). This incision left a record of stepped valley-border landforms and deposits associated with the development of the Rio Grande valley (e.g., Gile et al. 1981; Connell et al. 2007a).

In the Albuquerque Basin, the top of the Santa Fe Group is locally marked by relict basin-floor surfaces, such as the Llano de Albuquerque geomorphic surface (Machette 1985). The Llano de Albuquerque is a broad south-trending tableland between the Rio Grande and Rio Puerco valleys (Fig. 1). Petrocalcic soils associated with this surface commonly possess stage III+ pedogenic carbonate morphology (Machette et al. 1997); stage IV morphology is locally recognized in shallow excavations (Connell, unpubl. data). A few remnants of degraded petrocalcic soils are found near La Ceja (Fig. 1). Other constructional surfaces, such as the Sunport and Llano de Manzano surfaces (Fig. 1), locally mark the top of the Sierra Ladrones Formation and younger deposits (Lambert 1968; Machette 1985). These surfaces have been interpreted to represent local constructional tops of the Santa Fe Group that were abandoned by continued differential basin subsidence and fault activity (Connell et al. 2000, 2001), whereas Cole et al. (2007) attribute these younger surfaces to the geomorphic expression of younger inset fill terraces.

The stratigraphic nomenclature of the Santa Fe Group in the Albuquerque Basin has a long and complicated history. Connell (2004) provides a summary of the stratigraphic nomenclature of the Albuquerque Basin based on work conducted between 1996 and 2001. The development of stratigraphic nomenclature summarized by Connell (2004) is reviewed and expanded below (Fig. 2). Important early studies of the Santa Fe Group in the Albuquerque Basin began with the work of Kirk Bryan and his students (Bryan and McCann 1937, 1938; Wright 1946). They proposed a three-part stratigraphic subdivision for the area. These units are, in ascending stratigraphic order: lower gray, middle red, and upper buff members of their Santa Fe Formation (Fig. 2A). Ted Galusha (1966) subsequently assigned the lower gray to the Zia (Sand) Formation and subdivided it into the Piedra Parada and Chamisa Mesa Members. Gawne (1981) named the Cañada Pilares Member of the Zia Formation for an interval of red claystone and sandstone between the Chamisa Mesa Member and overlying deposits that were later considered by R. H. Tedford and colleagues to be an unnamed (upper) member of the Zia Formation (Fig. 2B; Tedford and Barghoorn 1997; Beckner and Mozley 1998). Connell et al. (1999) referred to this upper, unnamed member as the Cerro Conejo Member of the Zia Formation (Fig. 2D).

Connell et al. (1999) proposed the Arroyo Ojito Formation (Fig. 2D) for exposures in Arroyo Ojito, just north of La Ceja (Fig. 1). Other workers adopted this nomenclature with modifications (Fig. 2B, E, and F). A problem with the implementation of this stratigraphic nomenclature occurred because of noteworthy ambiguities regarding unit mappability and the uncertain stratigraphic position of the middle red formation or member (Fig. 2A, C, and F; Spiegel 1961; Lambert 1968; Williams and Cole 2005, 2007). Connell et al. (1998) named the Atrisco Member for a unit in the middle red formation (Fig. 2C). The Atrisco Member was thought to underlie the Sierra Ladrones Formation, a unit named by Machette (1978) for fluvial deposits in the southern Albuquerque Basin. The compilation of the Albuquerque 30′ x 60′ quadrangle (Williams and Cole 2005, 2007) adopted, with modifications, parts of the nomenclature proposed by Connell et al. (1999). The Albuquerque quadrangle compilation included the middle red formation of Bryan and McCann (1937) for units assigned to the Arroyo Ojito Formation Connell et al. (1999).

Generalized geologic map

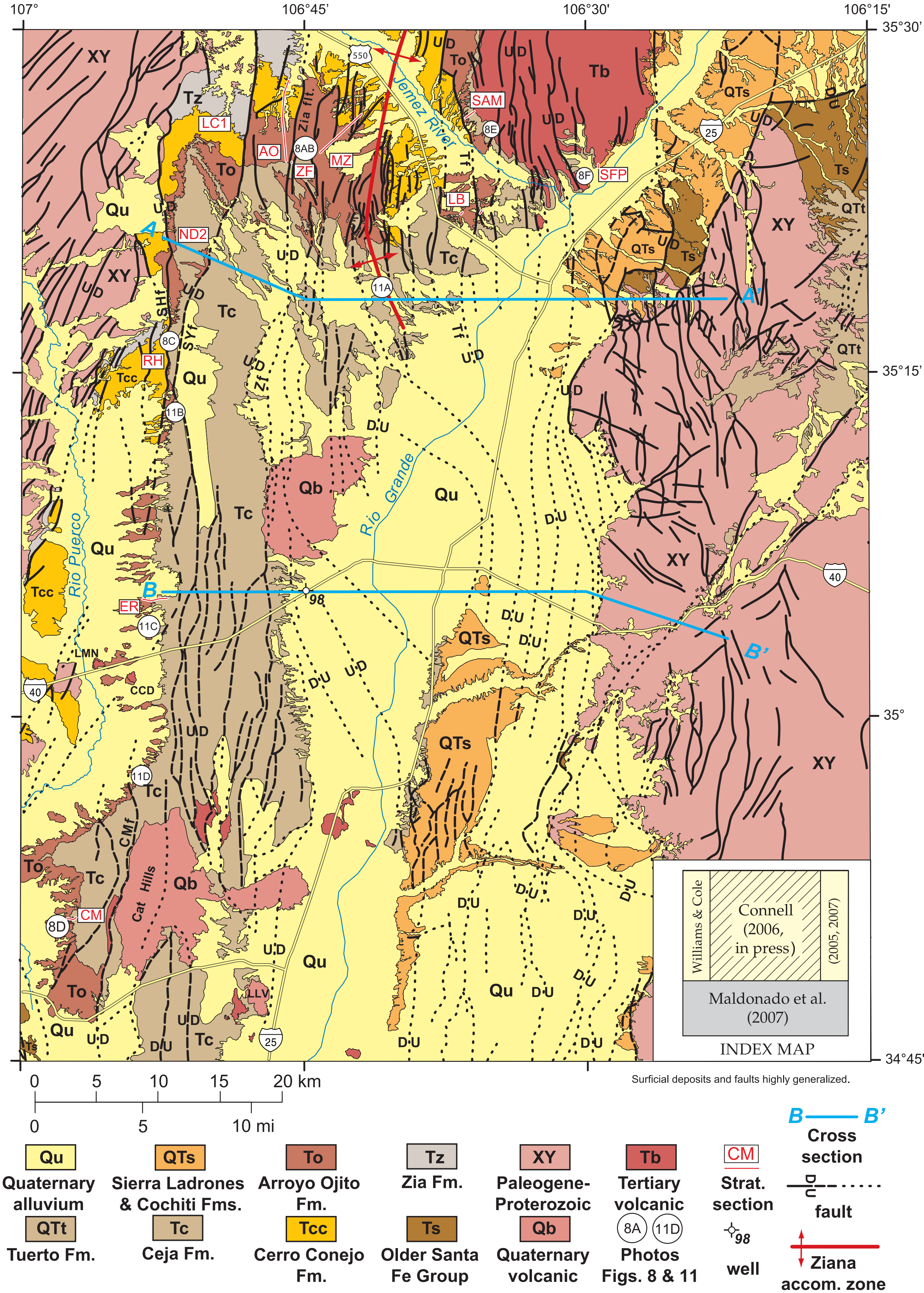
Recent geologic studies of the Albuquerque Basin resulted in the production of many geologic maps that have been released by the New Mexico Bureau of Geology and Mineral Resources (http://geoinfo.nmt.edu/statemap/home.html) and the U.S. Geological Survey (http://nm.water.usgs.gov/mrg/). Three geologic map compilations have already resulted from these intensive regional studies (Williams and Cole 2005, 2007; Connell 2006, in press; Maldonado et al. 2007). The treatment of the stratigraphy of the Albuquerque Basin varies among these compilations. The spatial distributions of formations portrayed in the simplified geologic map of the study area (Fig. 3) were generalized by comparing units (Table 1) in two of the aforementioned compilations to Connell (2006, in press). Geologic cross sections (Fig. 4) are generalized from Connell (2006, in press) and aid in portraying the stratigraphic position of the formation- and member-rank units described in this paper.

Methods

The lithostratigraphic units revised and defined here are in accordance with the North American Stratigraphic Code (NACSN 2005). According to the NACSN, lithostratigraphic units are defined with appropriate stratotypes. The stratigraphic names proposed herein were checked using the U.S. Geological Survey National Geologic Lexicon Database (GEOLEX 2007).

Stratigraphic type and reference sections were measured and described using a Jacob staff and Abney level. Descriptions of these stratigraphic sections are shown in the appendices. The base or top of stratigraphic sections was surveyed using a hand-held, nondifferentially corrected global positioning satellite unit. Deposit colors were described using Munsell (1992) notation. Sedimentary structures and textures were described using methods dis-

FIGURE 3—Simplified geologic map of the central Albuquerque Basin, depicting stratigraphic sections and localities discussed in this study. Circled alphanumeric locations (e.g., Figs. 8A, B and 11A) correspond to photographs in Figures 8 and 11, respectively. Surficial deposits are not differentiated. Faults are diagrammatically portrayed and show relative up (**U**) and down (**D**) separation; they are dashed where approximate and dotted where buried. Crosscutting fault relationships in surficial deposits are not implied. Miocene basaltic lavas of La Mesita Negra (**LMN**) and the Cerro Colorado dacite (**CCD**) are within the Navajo Draw Member. Los Lunas volcano (**LLV**) is a Pleistocene volcanic center near the southern part of the study area. Simplified geologic cross sections are illustrated in Figure 4. Faults discussed in text include the Cat Mesa fault (**CMf**), Sand Hill fault (**SHf**), San Ysidro fault (**SYf**), Tanaya fault (**Tf**), and Zia fault (**Zf**).


107°
106°45'
106°30'
106°15'
35°30'
35°15'
35°
34°45'
XY
Tz
LC1
Zia flt.
AO
8AB
ZF
MZ
To
550
Jemez River
SAM
8E
Tb
QTs
25
Ts
QTt
8F
SFP
LB
Qu
ND2
A
A'
Tc
11A
SHf
SYf
8C
RH
Tcc
11B
ZYf
Tf
Qb
Rio Grande
Rio Puerco
B
B'
98
ER
11C
LMN
40
CCD
11D
CMf
Cat Hills
CM
8D
LLV
U D
D U
Williams & Cole
Connell (2006, in press)
(2005, 2007)
Maldonado et al. (2007)
INDEX MAP
Surficial deposits and faults highly generalized.
0 5 10 15 20 km
0 5 10 mi
Qu Quaternary alluvium
QTs Sierra Ladrones & Cochiti Fms.
To Arroyo Ojito Fm.
Tz Zia Fm.
XY Paleogene-Proterozoic
Tb Tertiary volcanic
CM Strat. section
B — B' Cross section
fault
QTt Tuerto Fm.
Tc Ceja Fm.
Tcc Cerro Conejo Fm.
Ts Older Santa Fe Group
Qb Quaternary volcanic
8A 11D Photos Figs. 8 & 11
98 well
Ziana accom. zone

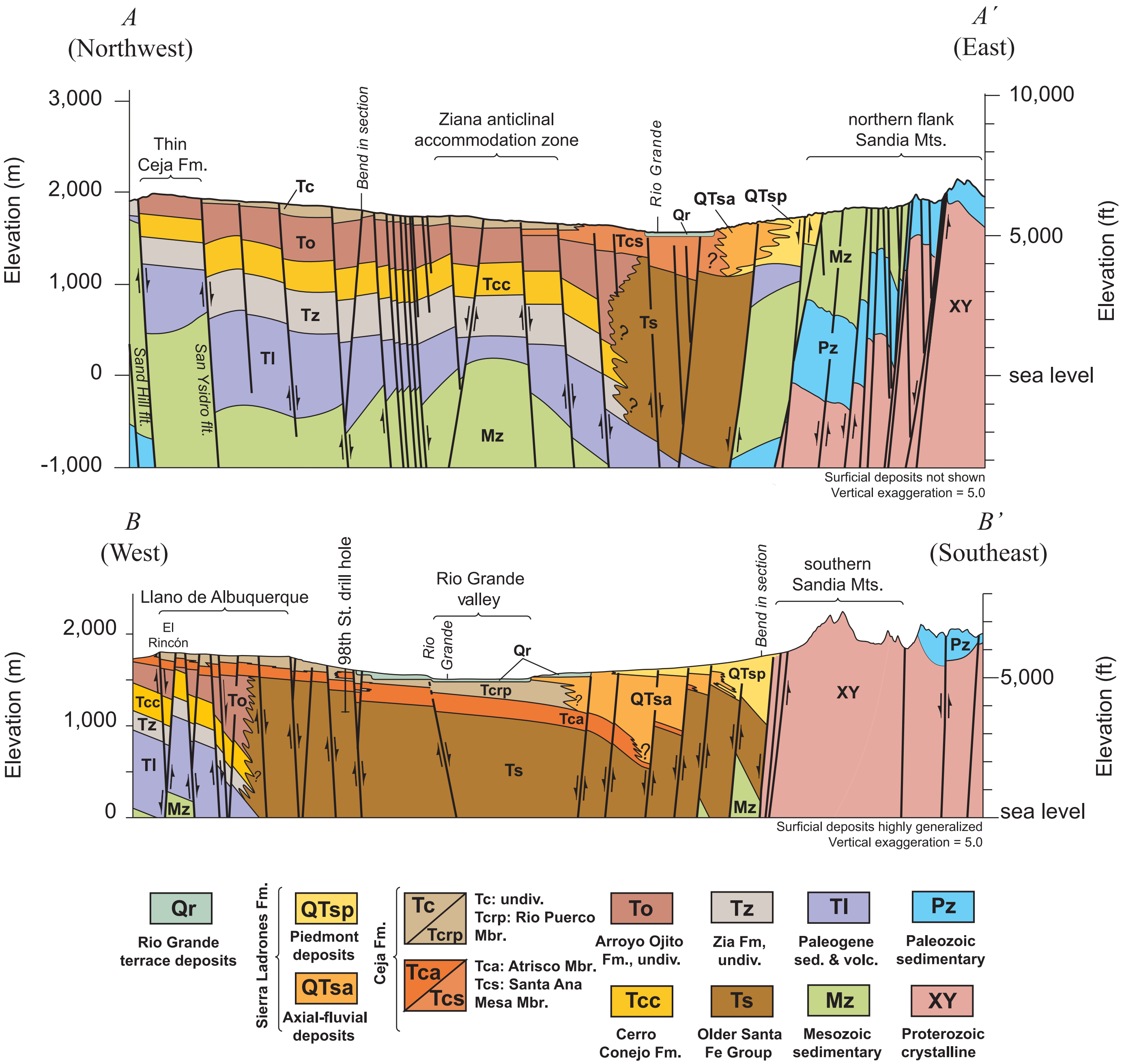


FIGURE 4—Simplified, vertically exaggerated geologic cross sections across part of the Albuquerque Basin (Fig. 3; modified after Connell 2006, in press). Surficial deposits not shown. *A–A′*—Geologic cross section across Ziana anticlinal accommodation zone and northern flank of Sandia Mountains. *B–B′*—Geologic cross section across basin near Ceja stratotype and southern Sandia Mountains. Cross sections depict a slightly angular relationship between overlying Ceja Formation (Tc, Tcrp, Tcs, and Tca) and Arroyo Ojito Formation (To) and undivided Santa Fe Group (Ts).

cussed in Compton (1985) and Dutro et al. (1989). Soil profiles were described using methods and nomenclature described in Birkeland (1999). The Ceja type section at El Rincón (Kelley 1977) was redescribed and extended downsection. Stratigraphic sections of Soister (1952), Connell et al. (1999), and Brandes (2002) have been reinterpreted and generalized where appropriate.

Cerro Conejo Formation

The Cerro Conejo Formation is a succession of very pale brown to pink and yellowish-red, well-sorted, fine- to medium-grained, medium- to thick-bedded, locally cross-stratified, tabular sandstone, with minor thinly bedded mudstone interbeds (Fig. 5; units 3–8 of Connell et al. 1999). Gravel is essentially nonexistent in the type area; however, thin lenses of chert- and volcanic-pebble-bearing conglomerate in the upper 30 m are recognized along the northern Ceja del Rio Puerco (Tedford and Barghoorn 1999). The lower part of the Cerro Conejo contains abundant calcium-carbonate cemented concretions (Beckner and Mozley 1998); the upper part is coarser-grained sand and contains fewer concretionary intervals. The Cerro Conejo Formation includes abundant white to light-greenish-gray volcanic ash beds, many of which have been altered to clay. The Cerro Conejo Formation records a transition from the predominantly eolian and interdune lacustrine and fluvial environments of the Cañada Pilares, Chamisa Mesa, and Piedra Parada Members of the Zia Formation to sandy and gravelly fluvial deposits of the overlying Arroyo Ojito Formation (Connell et al. 1999). The Cerro Conejo Formation is 316 m thick at the type section. It is 245–345

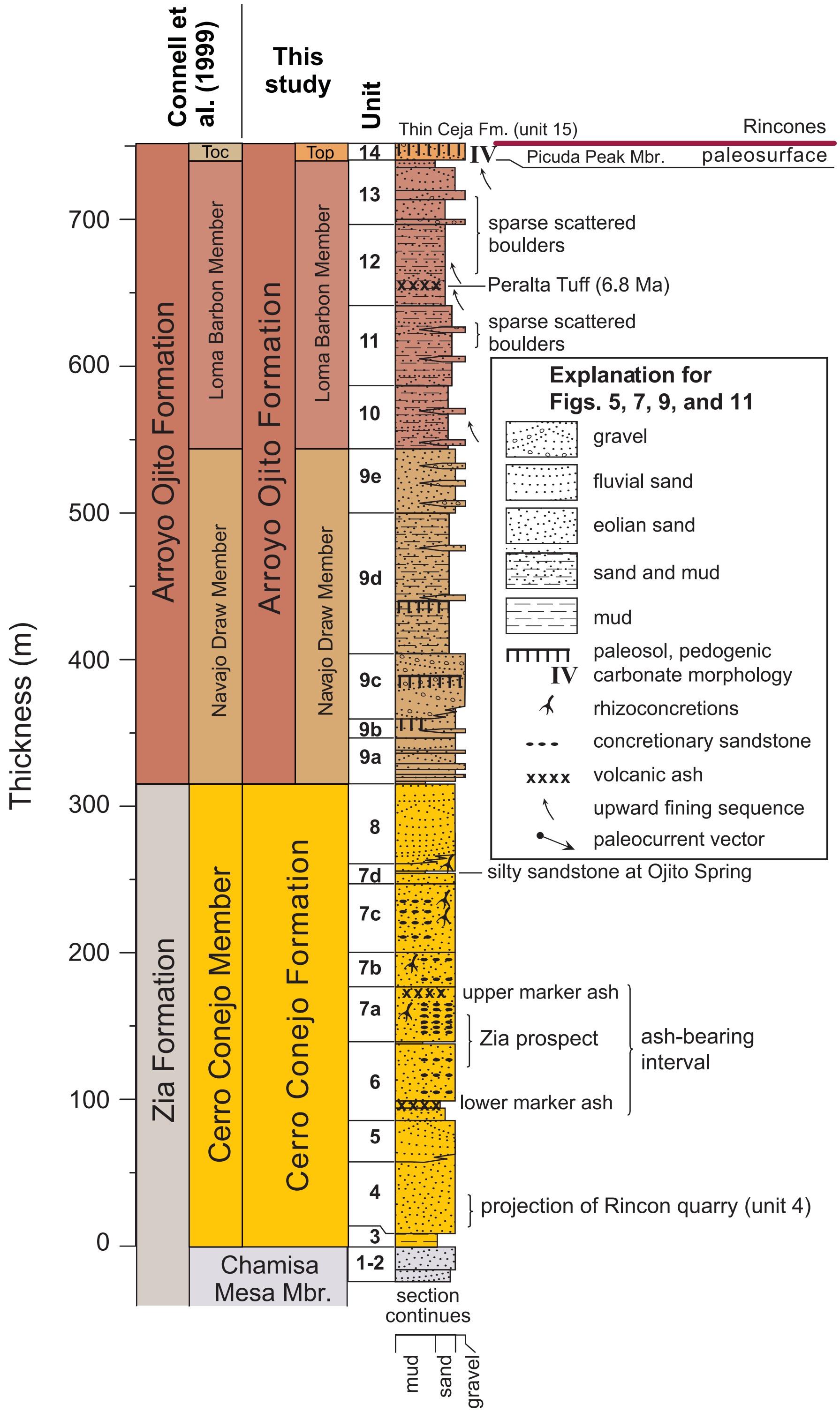


FIGURE 5—Reinterpreted type sections of the Cerro Conejo and Arroyo Ojito units proposed by Connell et al. (1999) at the Arroyo Ojito stratotype (**AO**, Fig. 3). The location of Galusha's (1966) Rincon quarry and Zia prospects are shown in column. Red line denotes Rincones paleosurface. The Ceja Formation is less than 1 m thick.

m thick along the Ceja del Rio Puerco (Tedford and Barghoorn 1999). The Cerro Conejo overlies the Chamisa Mesa and Cañada Pilares Members of the Zia Formation and is overlain by, and interfingers with, the basal Navajo Draw Member of the Arroyo Ojito Formation (Figs. 2G, 4 and 5). North of the Rio Puerco valley, basaltic lavas at Chamisa Mesa (Fig. 1) overlie the Cerro Conejo Formation. The basalt of Chamisa Mesa (part of the Paliza Canyon Formation) yielded a whole-rock K-Ar age of 10.4 ± 0.5 Ma (Luedke and Smith 1978).

The history of stratigraphic usage of the Cerro Conejo Formation is complicated and requires elucidation. Early workers (Bryan and McCann 1937; Kelley 1977) considered these beds to be part of the middle red member of their Santa Fe Formation (Fig. 2A). Tedford and Barghoorn (1997) initially assigned the Cerro Conejo to the Zia Formation, but they subsequently placed it in the Arroyo Ojito Formation (Tedford and Barghoorn 1999) based on an unconformity inferred near the base (Fig. 2E). Connell et al. (1999) proposed assignment of the Cerro Conejo to the Zia Formation (Fig. 2D) because of previous usage (i.e., Tedford and Barghoorn 1997), compositional similarity (mostly lithic arkose), interpreted depositional environments (eolian and fluviatile), and also because the lateral (mappable) extent of this unit was not sufficiently established by 1999. Williams and Cole (2005, 2007) considered the Cerro Conejo as a member of their "Middle red" formation (Fig. 2F).

The stratigraphic placement of the Cerro Conejo by Tedford and Barghoorn (1999) was largely based on a magnetostratigraphically defined lacuna between the Cerro Conejo and Chamisa Mesa units. This lacuna, defined where polarity chron 5B is interpreted to be missing, represents a hiatus of 1.6–1.0 m.y. in duration (Fig. 6; Tedford et al. 2004). This basal disconformity is somewhat cryptic but separates the lower well-cemented and cross-stratified eolianite of the Chamisa Mesa Member from the overlying tabular sandstone and thin to medium interbedded mudstone of the fluvial and eolian Cerro Conejo Formation. The Cañada Pilares Member is missing at the type section, indicating either that this member is discontinuous or it has been eroded.

The location of this basal disconformity was poorly constrained during the studies that led up to the earlier stratigraphic characterization of Connell et al. (1999). In fall of 1999, Richard Tedford, Steven Barghoorn, and the author were able to relocate Galusha's (1966) age-diagnostic (late Barstovian) Rincon quarry in unit 4 of the Cerro Conejo type section (Figs. 5 and 6). The location of the Zia prospect is still poorly constrained stratigraphically, because a relatively short normal fault cuts the area described by Galusha. This prospect is in unit 6 or 7 at the type section. Placement of the Rincon quarry near the base of the type Cerro Conejo provides an important biostratigraphic constraint on the location of the disconformity reported by Tedford and Barghoorn (1999). The Cañada Pilares Member is missing at the Cerro Conejo type section, supporting erosion of the Cerro Conejo/Chamisa Mesa contact. The Cerro Conejo is quite mappable and has been delineated across much of the northwestern flank of the Albuquerque Basin (e.g., Williams and Cole 2005, 2007). The Cerro Conejo is lithologically distinct from the overlying gravel- and mudstone-bearing deposits of the fluviatile Arroyo Ojito Formation (Connell et al. 1999). Thus, lithologic distinctiveness, thickness, overall mappability (Fig. 3), and the presence of a basal disconformity support elevating the Cerro Conejo to formation rank (Fig. 2G).

Biostratigraphy, magnetostratigraphy, tephrochronology, and radioisotopic dating constrain deposition of the Cerro Conejo Formation to ~14.6–9.5 Ma (Fig. 6). The location of Rincon quarry in the type section and results from the magnetostratigraphic study by Tedford and Barghoorn (1999) constrain the age of the lower Cerro Conejo Formation between 14.6 and 12.5 Ma (Fig. 6; Tedford et al. 2004). Late Barstovian fossils have been described in the Cerro Conejo Formation in the Rio Puerco valley (Tedford and Barghoorn 1999; Morgan and Williamson 2000). The upper part of the Cerro Conejo Formation contains Clarendonian mammalian remains, which extend the upper age to approximately 10.0 Ma (Fig. 6; Santa Ana Wash sites, Tedford et al. 2004). Some of the Cerro Conejo ashes have been correlated with 10.8–11.3 Ma tephra from the Trapper Creek sequence from Utah and northeastern Nevada (Personius et al. 2000; Koning and Personius 2002). A tephra layer found along the Ceja del Rio Puerco yielded a single-crystal K-Ar age (on biotite) of 13.6 ± 0.1 Ma (Tedford and Barghoorn 1999). Nearly all of the Cerro Conejo Formation is overlain by basaltic lava flows in the Paliza Canyon Formation of the southern Jemez Mountains (Chamberlin et al. 1999; also see Connell 2004, pp. 370–371, and references therein). These Paliza Canyon basaltic lavas yielded $^{40}Ar/^{39}Ar$ ages ranging from 9.8 to 9.2 Ma (R. M. Chamberlin, unpubl. data).

Because the Arroyo Ojito–Cerro Conejo contact interfingers to the east, a precise age of the youngest Cerro Conejo Formation is locally difficult to determine. For example, exposures of granite-bearing quartzo-feldspathic tabular sandstone reported near Loma Creston (Fig. 1) were mapped by Chamberlin et al. (1999, unit Tsf(s)). These deposits extend approximately 50 m above the Paliza Canyon Formation lava flows and may represent either the highest beds of the Cerro Conejo Formation or the lowest part of the Arroyo Ojito Formation. If these sandstones are part of the upper Cerro Conejo, they are the youngest occurrences of this unit known to date.

Arroyo Ojito Formation

The Arroyo Ojito Formation is a nearly 500-m-thick succession of fluviatile deposits exposed in the northwestern part of the Albuquerque Basin. Deposits of the Arroyo Ojito Formation are derived from streams draining the southeastern Colorado Plateau, San Juan Basin, and Sierra Nacimiento (Connell et al. 1999; Brandes 2002). The Arroyo Ojito Formation overlies the Cerro Conejo Formation and is unconformably overlain by the Ceja Formation (Figs. 4 and 5). Connell et al. (1999) divided the Arroyo Ojito Formation into the Navajo Draw, Loma Barbon, and Ceja Members (Fig. 2D). The Ceja has been raised to formation rank (see below). The age of the Navajo Draw Member is constrained by a basaltic lava flow at La Mesita Negra (LMN, Fig. 3) that yielded a whole-rock $^{40}Ar/^{39}Ar$ age of 8.11 ± 0.05 Ma (Fig. 6; Maldonado et al. 2006, location 13, table 1). The overlying Loma Barbon Member contains 6.8–7.1-Ma tephra correlated to the Peralta Tuff Member of the Bearhead rhyolite (Fig. 6; see Connell 2004 and references therein). A red dacitic vent called Cerro Colorado is exposed along the eastern margin of the Rio Puerco valley (CCD, Fig. 3). The base of this edifice is within the Navajo Draw Member. A single-crystal $^{40}Ar/^{39}Ar$ age on sanidine of 7.11 ± 0.46 Ma (NMGRL 8945 and 8946, W. C. McIntosh, unpubl. data) indicates temporal overlap with the Peralta Tuff in the Loma Barbon Member. This overlapping range of ages suggests that the Navajo Draw/Loma Barbon contact is about 6.8–7.6 Ma. The presence of approximately 100 m of Loma Barbon deposits above the Peralta Tuff beds in the Arroyo Ojito type area would require an unusually high rate of deposition of more than 500 m/m.y. It is more likely that these two members interfinger and that deposition of the upper Navajo Draw Member was coeval with the lower Loma Barbon Member in the Rio Puerco valley.

The Ceja Member of Kelley (1977) was initially included in the Arroyo Ojito Formation because of the similarity in gravel composition, paleocurrent directions, and interpreted source area (Connell et al. 1999; Brandes 2002; Connell 2004). Recognition of the Rincones paleosurface (see below) and abandonment of the Pantadeleon Formation (see below) require the definition of a new lithostratigraphic term for the upper Arroyo Ojito Formation. (Fig. 2G).

Picuda Peak Member (new name)

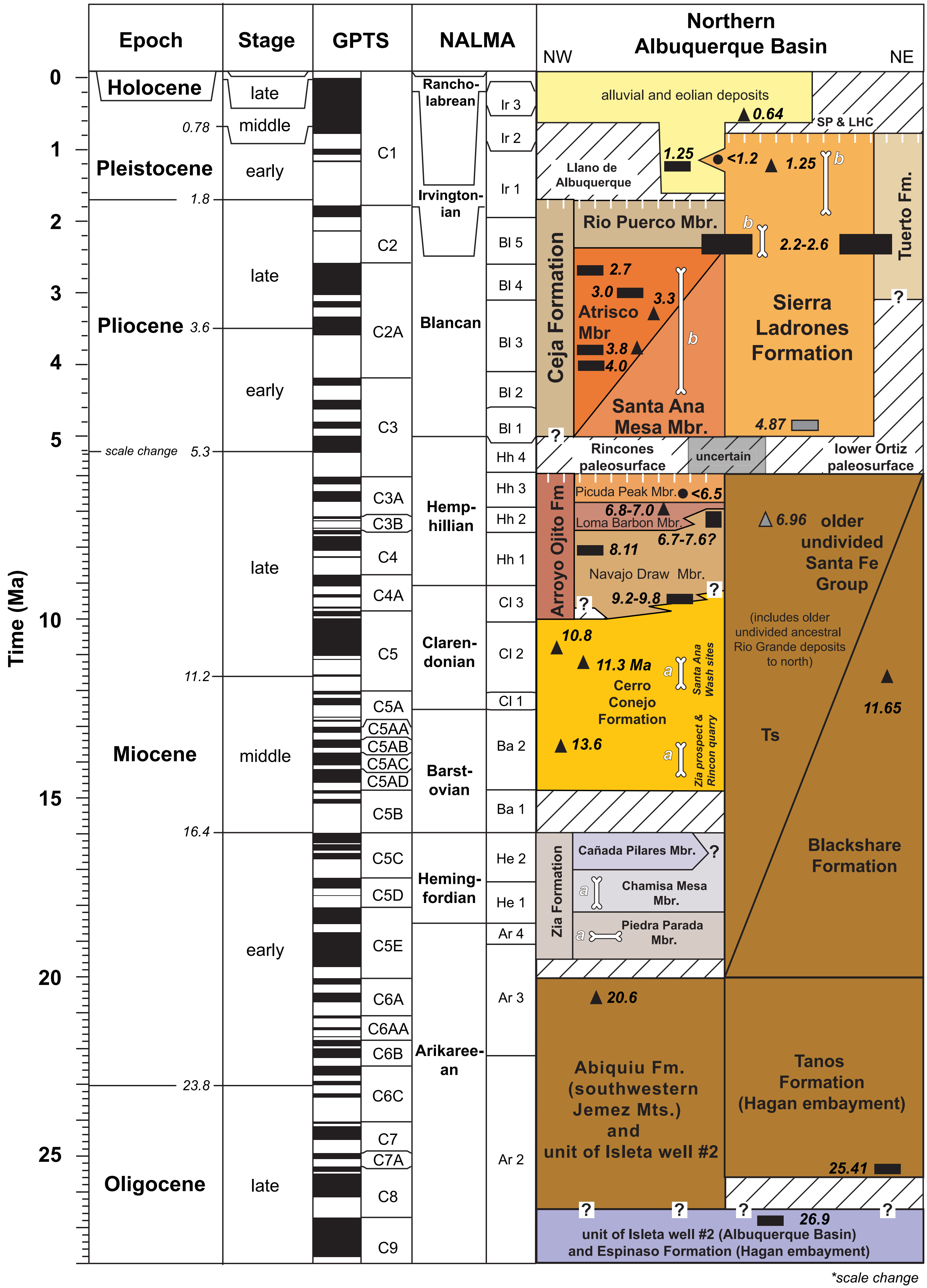
The Picuda Peak Member is herein proposed for the highest member of the Arroyo Ojito Formation at the Arroyo Ojito stratotype of Connell et al. (1999). The Picuda Peak Member replaces their Ceja Member (of the Arroyo Ojito Formation) at the Arroyo Ojito type section (Fig. 5). The Picuda Peak Member is named for conglomeratic deposits near Picuda Peak, a low hill on the Bernalillo NW quadrangle in Sandoval County (Fig. 1). The Picuda Peak type section (Fig. 7, MZ), approximately 8 km north-northwest of Picuda Peak, is modified from Brandes (2002). She assigned these deposits to the Ceja Member of the Arroyo Ojito Formation (sensu Connell et al. 1999). These deposits are now assigned to the Picuda Peak Member (Fig. 2G).

The Picuda Peak Member is 50 m thick at the type section (Appendix A) but is no more than 10 m thick at the Arroyo Ojito type section (Fig. 7). The Picuda Peak Member marks the top of an overall upward-coarsening trend in the Arroyo Ojito Formation. It conformably overlies the Loma Barbon Member at the Arroyo Ojito type section but forms a sharp boundary with slight angular discordance to the east, near the Ziana anticlinal accommodation zone (Figs. 3 and 4; Koning and Personius 2002). It is not exposed east of this structural zone. The boundary between these two units is placed at the base of an abrupt upward coarsening of reddish-yellow conglomerate at the Picuda Peak and Arroyo Ojito sections.

Picuda Peak deposits contain pinkish-gray to light-brown and reddish-yellow (5YR-7.5YR 6/2-6/6) sandy conglomerate and cobbly to bouldery sandstone interbedded with yellowish-red (5YR 5/8) sandstone and reddish-yellow to brownish-yellow muddy sandstone (Fig. 8A). Sandstone is fine to coarse grained, generally very thinly to medium bedded, and feldspathic in composition (Koning and Personius 2002). Picuda Peak conglomerate contains abundant volcanic and red granitic and gneissic rocks with minor sandstone, chert, and orthoquartzite (Brandes 2002). The Picuda Peak Member is distinguished from the Ceja Formation by color and stratigraphic position (Figs. 4, 5, and 7). The Picuda Peak Member is typically redder in color (5-7.5YR hues) than the pale- to yellowish-brown (5-10YR hues) colors of the Ceja Formation. Gravel composition in the Picuda Peak Member is typically less diverse than in the overlying Ceja Formation. The upper contact is locally marked by a petrocalcic soil associated with the Rincones paleosurface (Fig. 8A).

The Picuda Peak Member is late Miocene in age. The basal contact of the Picuda Peak Member sits approximately 100 m above an interval of fallout ashes that range in age from 6.8 to 7.1 Ma (sanidine $^{40}Ar/^{39}Ar$ ages; Connell et al. 1999; Koning and Personius 2002). A fluvially recycled basaltic cobble sampled by the author and Dan Koning, approximately 20 m below the top of the

FIGURE 6—Age and correlation of revised stratigraphy in the northern Albuquerque Basin (Fig. 2, **Column G**), including selected age-control points. The Llano de Albuquerque, Sunport (**SP**), and Las Huertas (**LHC**) geomorphic surfaces represent local depositional tops of the Santa Fe Group. Black rectangles denote dated lava flows; black triangles denote dated tephra; black circles denote dated reworked cobbles. Biostratigraphic data sources (shown by bone symbol; length depicts approximate age range) from: (a) Tedford et al. (2004) and (b); Morgan and Lucas (2003). Numerical age control points from Connell (2004, 2006, and in press); Connell et al. 1999, 2002, 2005, and 2007a, b); Maldonado et al. (2006, 2007); Tedford et al. (2004); and unpublished data. Gray symbols denote age-control points taken from outside of study area (Bachman and Mehnert 1978; Smith et al. 2001). Figure produced with TS-Creator (2007). **NALMA** refers to North American Land Mammal Ages. **GPTS** refers to the geomagnetic polarity time scale. The base of the Ceja Formation is diachronous.


Epoch
Stage
GPTS
NALMA
Northern Albuquerque Basin
NW
NE
Time (Ma)
0
1
2
3
4
5
10
15
20
25
Holocene
Pleistocene
Pliocene
Miocene
Oligocene
late
middle
early
late
early
late
middle
early
late
0.78
1.8
3.6
scale change
5.3
11.2
16.4
23.8
C1
C2
C2A
C3
C3A
C3B
C4
C4A
C5
C5A
C5AA
C5AB
C5AC
C5AD
C5B
C5C
C5D
C5E
C6A
C6AA
C6B
C6C
C7
C7A
C8
C9
Rancho-labrean
Irvington-ian
Blancan
Hemp-hillian
Claren-donian
Barst-ovian
Heming-fordian
Arikaree-an
Ir 3
Ir 2
Ir 1
Bl 5
Bl 4
Bl 3
Bl 2
Bl 1
Hh 4
Hh 3
Hh 2
Hh 1
Cl 3
Cl 2
Cl 1
Ba 2
Ba 1
He 2
He 1
Ar 4
Ar 3
Ar 2
alluvial and eolian deposits
0.64
SP & LHC
Llano de Albuquerque
1.25
<1.2
1.25
b
Tuerto Fm.
Ceja Formation
Rio Puerco Mbr.
b
2.2-2.6
2.7
3.0
3.3
Atrisco Mbr
3.8
4.0
b
Sierra Ladrones Formation
?
Santa Ana Mesa Mbr.
4.87
?
Rincones paleosurface
uncertain
lower Ortiz paleosurface
Arroyo Ojito Fm
Picuda Peak Mbr.
<6.5
6.8-7.0
Loma Barbon Mbr.
6.7-7.6?
8.11
Navajo Draw Mbr.
?
9.2-9.8
?
6.96
older undivided Santa Fe Group
(includes older undivided ancestral Rio Grande deposits to north)
10.8
11.3 Ma
a
Santa Ana Wash sites
Cerro Conejo Formation
11.65
Ts
13.6
a
Zia prospect & Rincon quarry
Zia Formation
Cañada Pilares Mbr.
?
a
Chamisa Mesa Mbr.
a
Piedra Parada Mbr.
Blackshare Formation
20.6
Abiquiu Fm. (southwestern Jemez Mts.) and unit of Isleta well #2
Tanos Formation (Hagan embayment)
25.41
?
?
?
26.9
?
unit of Isleta well #2 (Albuquerque Basin) and Espinaso Formation (Hagan embayment)
*scale change

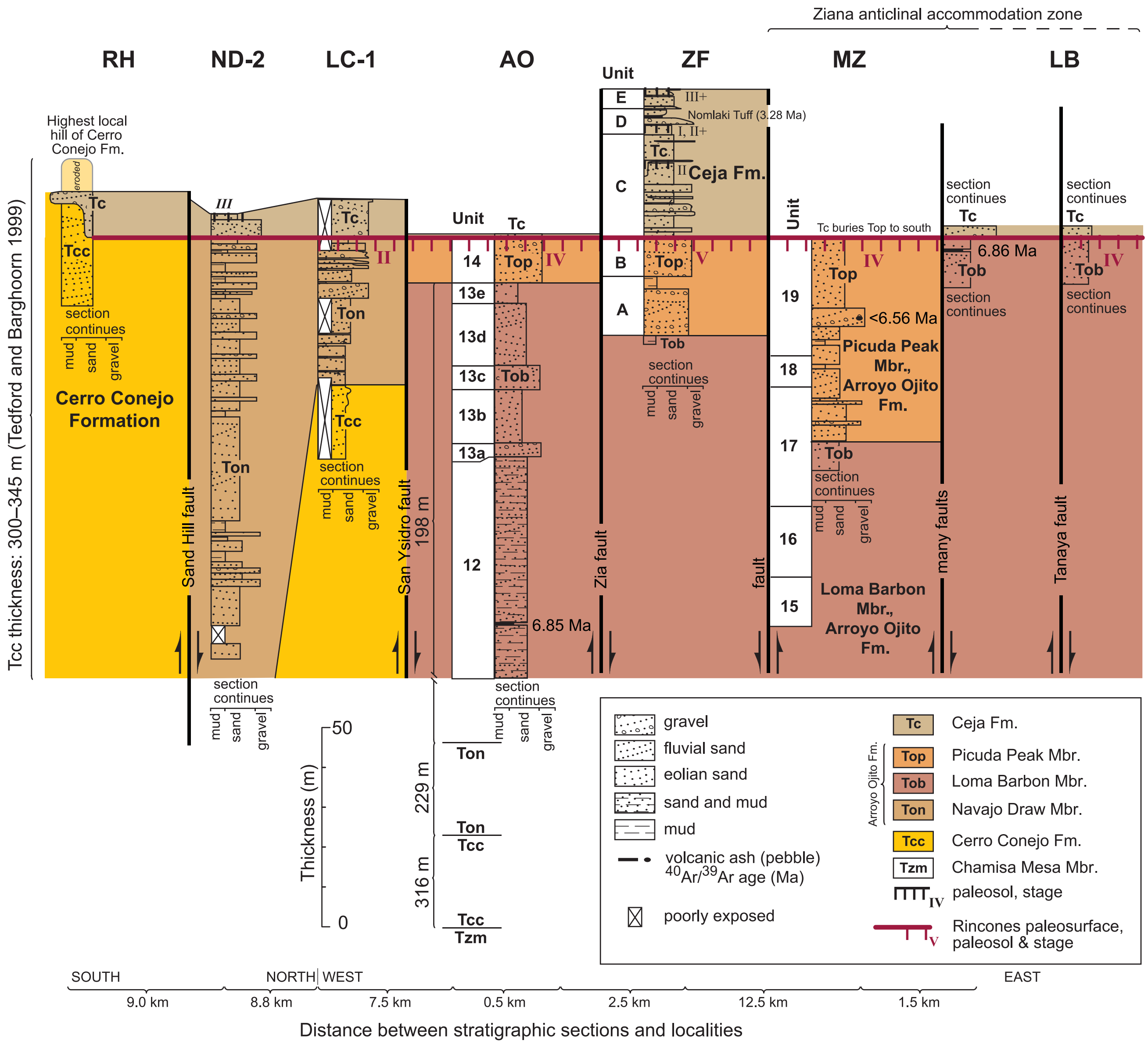


FIGURE 7—Stratigraphic sections illustrating relationships among sites along the Ceja del Rio Puerco and La Ceja (Fig. 3). Sites include Red Hill (**RH**), Navajo Draw (**ND-2**), La Ceja (**LC-1**), Arroyo Ojito (**AO**), Zia fault (**ZF**), Picuda Peak (**MZ**), and Loma Barbon (**LB**). Thick vertical lines depict major intrabasinal faults; arrows denote relative displacement. Brackets denote approximate deposit thickness (Brandes 2002; Connell et al. 1999; Tedford and Barghoorn 1999). Patterns, colors, and symbols described in Figure 5. The Picuda Peak type section was described by Brandes (2002, Marillo–Zia section). The red line denotes Rincones paleosurface.

Picuda Peak succession, yielded a whole-rock $^{40}Ar/^{39}Ar$ age of 6.56 ± 0.20 Ma (unit 18 of Brandes Marillo–Zia section; sample 8h-2 of Koning and Personius 2002). This date places a late Miocene maximum age of deposition for the top of the Picuda Peak Member. The upper capping soil exhibits stage V pedogenic carbonate morphology (Fig. 8A; Connell et al. 1999). The presence of such a strongly developed soil capping this unit suggests that this upper surface had been geomorphically stable for several hundred thousand years or longer (e.g., Machette 1985).

The Picuda Peak Member corresponds to the Ceja Member of Connell et al. (1999) and parts of the Ceja Member of Brandes (2002) and Koning and Personius (2002) on the Bernalillo NW quadrangle, and Ceja Formation on the Albuquerque 30′ x 60′ quadrangle by Williams and Cole (2005, 2007). The Picuda Peak Member also correlates to sand and gravel deposits of the western facies (Tub) of Spiegel (1961) and unit Tsus of Personius et al. (2000).

Ceja Formation (redefinition)

The Ceja Member (Formation) was named by Vincent Kelley (1977) for weakly consolidated sand and gravelly sand at the top of the Santa Fe Formation (Group, Fig. 2A). He considered the Ceja roughly equivalent to the upper buff member (Bryan and McCann 1937; Lambert 1968). Kelley designated the Ceja stratotype at the southern side of El Rincón, a semicircular drainage reentrant along the Ceja del Rio Puerco (Fig. 1). He extended the Ceja across the basin and into deposits now considered part of the Sierra Ladrones Formation (Lucas et al. 1993; Connell 2004). Connell et al. (1999) assigned the Ceja Member to the upper member of their Arroyo Ojito Formation and restricted it to fluvial deposits derived from the west (Fig. 2D). Member rank was proposed (at the time) to maintain compositional consistency and provenance of western-margin-derived fluvial deposits that encompassed the Arroyo Ojito definition of Connell et al. (1999).

The Ceja Formation typically contains a lower interval of interbedded sand and mud, and an upper interval that is predominantly sandy and pebbly to cobbly sand with scattered small boulders (Figs. 8C and 9). Deposits are light-yellowish-brown to reddish-yellow and pink, medium- to thick-bedded, fine- to very coarse grained sand, pebbly and cobbly sand, and minor reddish-brown to yellowish-red clay (Fig. 8A–D). The base of the Ceja is disconformable with the Arroyo Ojito Formation. It generally coarsens upsection and culminates with mesa-capping gravels that contain petrocalcic soils associated with the Llano de Albuquerque geomorphic surface.

The base of the Ceja Formation was not defined at the El Rincón stratotype. Lambert (1968) described 86 m of the upper buff formation, and Kelley (1977) described 64 m of the Ceja. The stratotype has been redescribed, and a new measured section has been extended to the Navajo Draw Member of the Arroyo Ojito Formation (Fig. 9). This revised stratotype is 94–104 m thick (Appendix B). The Ceja Formation locally contains rounded, white, micritic carbonate pebbles that are interpreted to be reworked from petrocalcic soils developed on the underlying Arroyo Ojito Formation. Williams and Cole (2005, 2007) reported an eastward shift in paleocurrent directions in the Ceja Formation compared to the underlying Arroyo Ojito Formation. Brandes (2002) compiled 110 paleocurrent observations for these deposits and found no obvious directional distinctions among these units.

Geologic maps document the lateral extent of the Ceja Formation in the central part of the Albuquerque Basin (e.g., Connell 2006, in press, Maldonado et al. 2007; Williams and Cole 2005, 2007). The subsurface extent of the Ceja Formation has been partly documented using well logs (Fig. 4; Connell et al. 1998; Connell 2006, in press). Based on well-log correlations in the Albuquerque area, the Ceja thickens from approximately 100 m near the Ceja del Rio Puerco to more than 420 m along the western margin of the Rio Grande valley (e.g., Gonzales #1 well, Connell et al. 1998). On Cat Mesa (Fig. 1), the Ceja Formation is 19 m thick (Fig. 9; Appendix C). The Ceja Formation thickens to the east and presumably interfingers with the Sierra Ladrones Formation (Fig. 4; Connell et al. 1998).

Fossil and radioisotopic data indicate that the Ceja Formation is Pliocene in age. At the Zia fault section of Connell et al. (1999), a fallout ash in the Ceja Formation was correlated to the ~3.28 Ma Nomlaki Tuff of the Tuscan and Tehama Formations, an ash from eastern California (see Connell et al. 1999). Deposits correlated to the Ceja Formation on Cat Mesa overlie the basaltic Cat Mesa lava flow (Fig. 8D; Maldonado et al. 2007). This flow yielded a whole-rock $^{40}Ar/^{39}Ar$ age of 3.00 ± 0.01 Ma (Maldonado et al. 2006). A younger basaltic lava in the Ceja succession (Black Mesa flow, Maldonado et al. 2007) yielded a whole-rock $^{40}Ar/^{39}Ar$ age of 2.68 ± 0.04 Ma (Maldonado et al. 2006). Pliocene lava flows at Santa Ana Mesa (San Felipe volcanic field, Kelley and Kudo 1978) locally overlie the Ceja Formation. A lava sampled from this volcanic field yielded a whole-rock K-Ar age of 2.5 ± 0.3 Ma (Bachman and Mehnert 1978). A fossil pocket gopher (*Geomys* sp.) was recovered from reddish-brown, muddy sandstone at the base of Loma Colorado de Abajo (Fig. 1). This species indicates a Pliocene (early or medial Blancan) age for these deposits (Fig. 6; Morgan and Lucas 2003).

Additional age constraints for the Ceja Formation come from correlations to other dated stratigraphic successions and volcanic units. The Sierra Ladrones Formation contains early Pleistocene fluvially recycled and primary fallout tephra derived from the Jemez volcanic field of northern New Mexico (~1.2–1.6 Ma, Connell 2004; Maldonado et al. 2007). These deposits overlie easternmost exposures of the Ceja Formation (Fig. 9). Other constraints come from Los Lunas volcano, near the southern end of the study area (Fig. 1; Maldonado et al. 2007). The youngest volcanic event overlies the Ceja Formation. Older lavas are interbedded within the Ceja Formation. These volcanic units yielded whole-rock $^{40}Ar/^{39}Ar$ ages of 1.25 ± 0.02 Ma and 3.80 ± 0.04 Ma, respectively (Maldonado et al. 2006). The oldest Ceja Formation is not well constrained because the deepest part of this unit is not exposed. It unconformably overlies the upper Miocene Picuda Peak Member, which has a maximum age of deposition of 6.56 Ma (see above). The Ceja thickens considerably to the east, indicating either faster rates of deposition, or older deposit ages.

Atrisco Member

Connell et al. (1998) provisionally proposed the Atrisco Member for a succession of reddish-brown mudstone and sandstone encountered in a core hole drilled near the intersection of 98th Street and I-40 in the town of Atrisco Grant (Fig. 1). This unit has a distinctive signature on borehole geophysical logs in many wells in southwestern Albuquerque, namely an increase in electrical conductivity and natural gamma ray log responses (Allen et al. 1998; Connell et al. 1998).

Connell et al. (1998) examined borehole geophysical logs and lithologic data from many wells in the Albuquerque area (Fig. 2C), where they recognized an interval of interbedded mudstone and sandstone having a sharp base (Fig. 4); however, the nature of the boundary was not determined because no core was recovered across this contact (Stone et al. 1998). The Atrisco Member was interpreted to mark the base of an overall upward-coarsening trend (Allen et al. 1998; Connell et al. 1998). Connell et al. (1998) suggested that this lower fine-grained interval might be exposed along the eastern escarpment of the Rio Puerco valley (Ceja del Rio Puerco, Fig. 1); however, geologic mapping had not confirmed this proposition yet. Later geologic mapping of the La Mesita Negra SE quadrangle by Shroba et al. (2003) delineated three units (Tms, Tps, and Tg) that document an overall upward-coarsening trend in their "upper Santa Fe Group sediments."

West of the Rio Grande, well-log data indicate that the top of the Atrisco Member is locally sharp where overlain by the Rio Puerco Member. East of the Rio Grande, the upper limit of the Atrisco Member is gradational and is interpreted to interfinger with the Sierra Ladrones Formation (Connell et al. 1998). The exposed boundary between the Atrisco Member and overlying Rio Puerco Member is gradational and interfingering at the stratotype along the Ceja del Rio Puerco (Fig. 9). This contact is sharp and disconformable near the Bernalillo–Sandoval County line, where a paleosol exhibiting stage III+ pedogenic carbonate morphology is preserved at the boundary (Fig. 8C). To the south, the Rio Puerco–Atrisco Member boundary becomes less distinctive.

At the type borehole the Atrisco Member is an 85–100-m-thick succession of brown, strong-brown to pink (7.5YR 5/4-7/4) and yellowish-brown to light-gray (10YR 5/4-5/6, 10YR 7/2), fine-grained, poorly sorted, massive to laminated, silty to clayey sandstone and mudstone (Connell et al. 1998; Stone et al. 1998). Stone et al. (1998) interpret deposition of the Atrisco Member in a fluvial environment with abundant, fine-grained, overbank sediments. The Atrisco Member is either truncated by faults or interfingers to the east with the Sierra Ladrones Formation (Fig. 4; Connell et al. 1998).

Connell et al. (1998) originally considered the Atrisco to be a member of the middle red formation of Bryan and McCann (1937; see also Lambert 1968; Fig. 2C). Connell (2004) placed this member into the upper part of the Arroyo Ojito Formation (Fig. 2D) in an attempt to reconcile stratigraphic correlation and nomenclatural problems and because the Ceja was considered a member-rank term of the Arroyo Ojito Formation at that time (Connell et al. 1999). Connell (2004) suggested that the Atrisco Member was either Miocene or Pliocene in age and was correlative to part of the Loma Barbon Member of the Arroyo Ojito Formation. The discovery of the Rincones paleosurface (see below) required adjustments to be made to the stratigraphic nomenclature of the Arroyo Ojito Formation. The presence of a disconformity that separates Miocene and Pliocene strata along the northwestern flank of the Albuquerque Basin is supported by interpretation of a sharp boundary in wells beneath Albuquerque (Allen et al. 1998; Connell et al. 1998). The mud-dominated unit between the upper gravel of the Ceja Formation and the underlying Rincones paleosurface is correlated to the Atrisco Member and is reassigned to a member of the Ceja Formation (Fig. 2G). The Atrisco Member can be distinguished

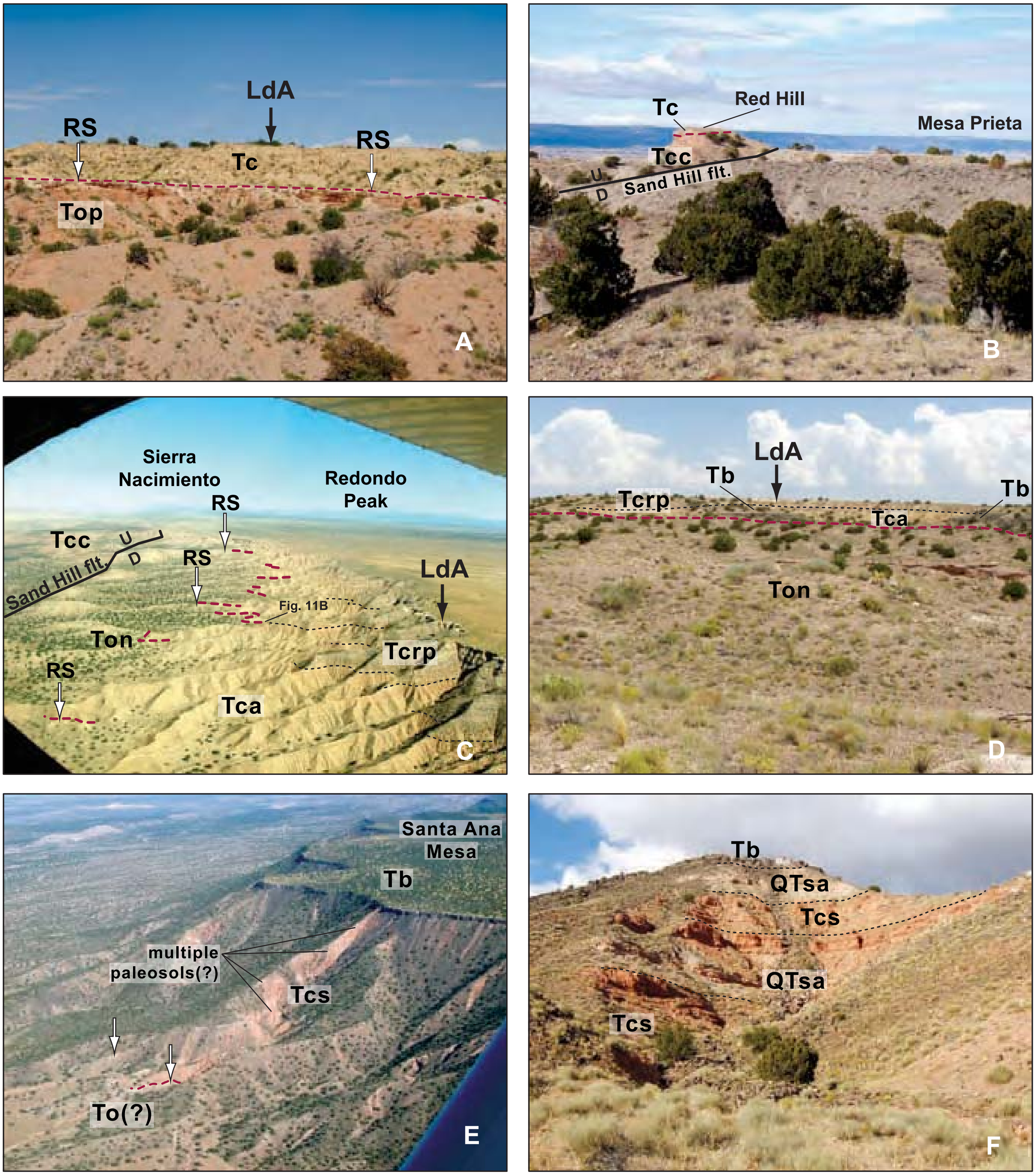


FIGURE 8—Photographs of the Ceja and Arroyo Ojito Formations. White arrow denotes petrocalcic soils of the Rincones paleosurface (**RS**, stage III+ or V pedogenic carbonate morphology); black arrow denotes petrocalcic soils of the Llano de Albuquerque (**LdA**, stage III+ morphology). Stratigraphic units include the Cerro Conejo Formation (**Tcc**), Navajo Draw Member (**Ton**), and Picuda Peak Member (**Top**) of the Arroyo Ojito Formation(**To**); Atrisco Member (**Tca**), Santa Ana Mesa Member (**Tcs**), and Rio Puerco Member (**Tcrp**) of the Ceja Formation (**Tc**); basaltic lava flows (**Tb**); and axial-fluvial member of the Sierra Ladrones Formation (**QTsa**). Thick red dashed line denotes the Rincones paleosurface. Dotted lines denote contacts between members of the Ceja Formation. Figure 3 illustrates approximate locations of stratigraphic sections and photographic locations. **A**—View to southeast of the stratigraphic succession of the Picuda Peak Member, Rincones paleosurface, and overlying Ceja Formation on hanging wall of Zia fault along La Ceja (**ZF**). **B**—View to northwest of Red Hill, where gravel of the Ceja Formation disconformably overlies the Cerro Conejo Formation. **C**—Aerial view to north along Ceja del Rio Puerco near the Bernalillo–Sandoval County line. The Cerro Conejo Formation (**Tcc**) is exposed on the footwall (west) of the Sand Hill fault. **D**—View of western edge of Cat Mesa (**CM**) showing stratigraphic position of Cat Mesa flow between the Ceja Formation and subjacent Navajo Draw Member (Fig. 9). **E**—Aerial view to north along western flank of Santa Ana Mesa showing reddish-brown sediments beneath upper Pliocene basaltic lava flows at Santa Ana Mesa. White arrows denote inferred boundary between probable Loma Barbon Member deposits and the overlying Santa Ana Mesa Member. White bands may represent probable buried calcic paleosols. **F**—View to northwest along southeastern flank of Santa Ana Mesa (Fig. 10) illustrating interbedded deposits of the Santa Ana Mesa Member of the Ceja Formation and axial-fluvial member of the Sierra Ladrones Formation.

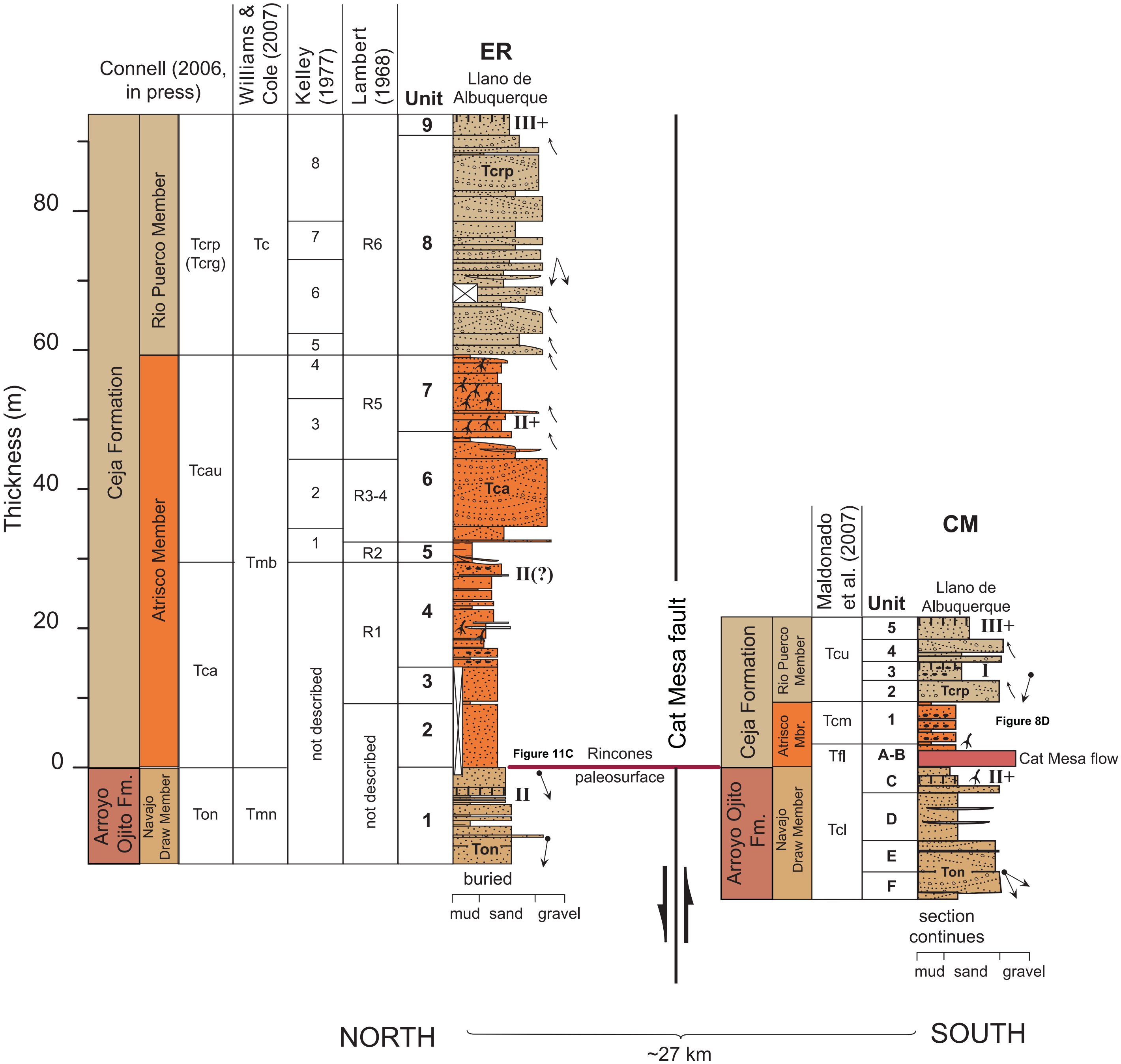


FIGURE 9—Stratigraphic sections illustrating the Ceja Formation type section at El Rincón (**ER**, Fig. 3) and reference section at Cat Mesa (**CM**, Fig. 3). Map units of Lambert (1968), Kelley (1977), Connell (2006), and Williams and Cole (2005, 2007) are shown in Table 1. The Cat Mesa lava flow is 3.00 Ma (Maldonado et al. 2006), rests on the Navajo Draw Member of the Arroyo Ojito Formation, and is overlain by the Atrisco and Rio Puerco Members of the Ceja Formation. The red line denotes Rincones paleosurface. Patterns and symbols described in Figure 5. Thick vertical lines depict major intrabasinal faults; arrows denote relative displacement.

from the Santa Ana Mesa Member by color and texture. The Atrisco Member is generally brownish in color, whereas the Santa Ana Mesa Member is chiefly red and yellowish-red in color.

In their compilation of the geology of the Albuquerque 30′ x 60′ quadrangle, Williams and Cole (2005, 2007) assigned the Atrisco Member to the "Middle red" formation (Fig. 2F). They interpret a disconformity between their Ceja Formation and the underlying Loma Barbon (Atrisco) member. Their mapped boundary, however, sits approximately 46–63 m above the Ceja–Navajo Draw boundary at El Rincón (Fig. 9).

Santa Ana Mesa Member (redefined)

The Santa Ana Mesa Member was proposed by Soister (1952) for conspicuous reddish-brown sandstone and conglomerate exposed beneath the flanks of Santa Ana Mesa (Fig. 8E). Basaltic lava flows of the late Pliocene San Felipe volcanic field cap this mesa (Kelley and Kudo 1978). Soister considered this unit to be correlative to Bryan and McCann's (1937) middle red member (Fig. 2A). He described a stratigraphic section along the western flank of Santa Ana Mesa (Fig. 10, Appendix D). His descriptions are rather broad, and the stratigraphic section cannot be precisely located; however, this section likely extended up the southwestern flank of Santa Ana Mesa. This stratigraphic section included "red beds of conglomerate, conglomeratic sandstone, sandstone, and siltstone" of his Santa Ana Mesa Member. His stratigraphic section extended down into "tan to brown

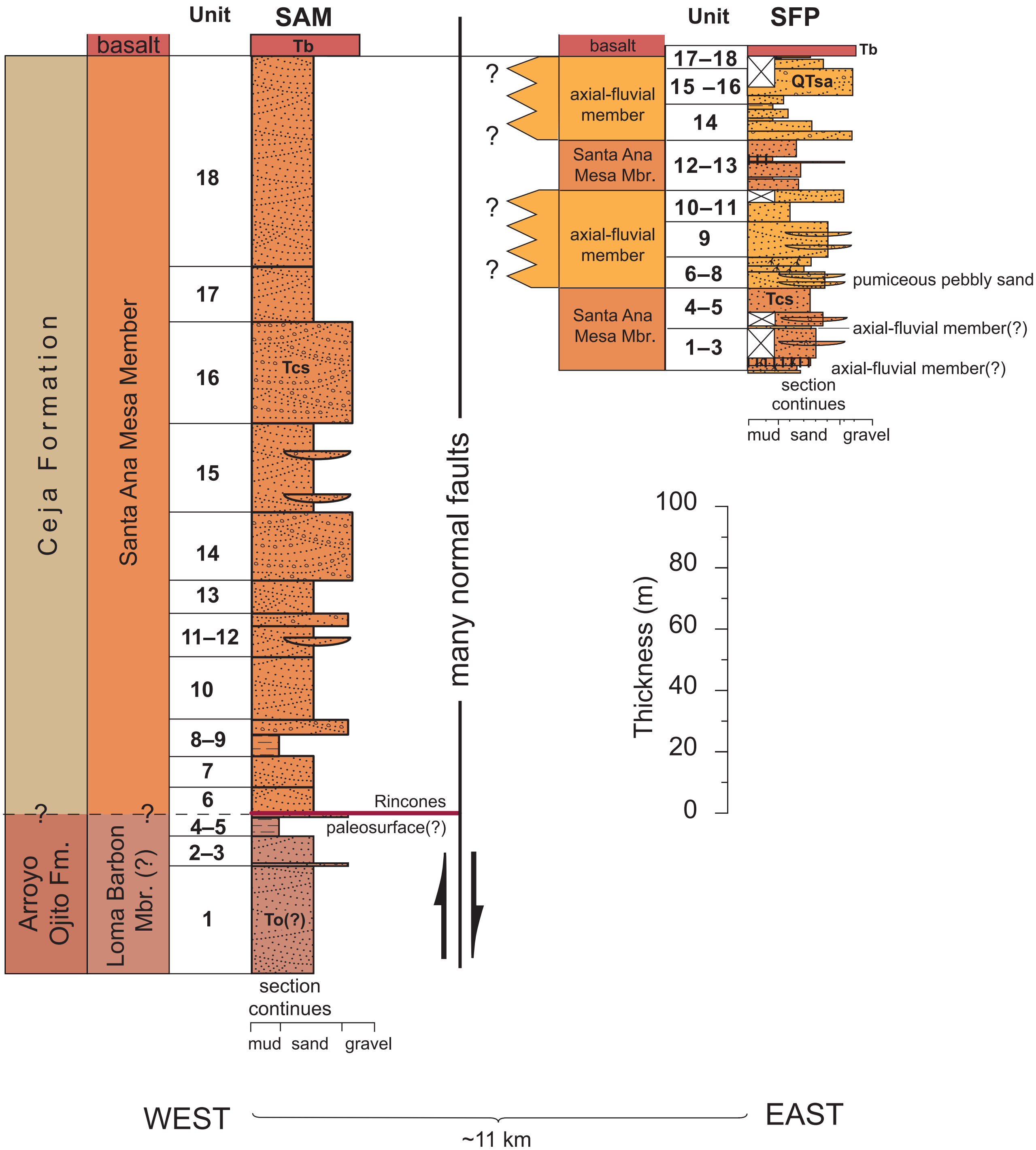


FIGURE 10—Stratigraphic sections of the Santa Ana Mesa Member of the Ceja Formation at the Santa Ana Mesa type area (Fig. 3). The western Santa Ana Mesa section (**SAM**) is designated as a provisional type section that was modified from a stratigraphic section of Soister (1952). A reference section along the southeastern flank of Santa Ana Mesa (**SFP**) was modified and reinterpreted after Brandes (2002). The red line denotes the Rincones paleosurface. Patterns and symbols described on Figure 5. Thick vertical lines depict major intrabasinal faults; arrows denote relative displacement.

beds of sandstone, conglomerate and volcanic fanglomerate" of his Bodega Butte Member. Some inconsistencies between the Santa Ana Mesa Member concept of Soister (1952) and subsequent geologic mapping arose because much of the recent mapping of the northern Albuquerque Basin had been completed before the stratigraphic nomenclature of Connell et al. (1999) was proposed, and key stratigraphic relationships were not known then. Personius (2002) extended the Arroyo Ojito Formation north of the Jemez River, but grouped these deposits into a single map unit containing the "Ceja and Loma Barbon members of Connell et al. (1999)." Personius (2002) delineated extensive basaltic colluvium that covers most of the flanks of Santa Ana Mesa and probably obscures much of this contact. The Tanaya fault (Tf, Fig. 3) is herein interpreted to juxtapose the Cerro Conejo Formation against the undivided Loma Barbon and Ceja units of Personius (2002). The lower part contains a 7.1 Ma pumice bed (Personius 2002). The upper part of this undivided unit extends up to the rim of Santa Ana Mesa and contains several strongly developed petrocalcic soils that possess stage III and IV pedogenic carbonate morphology (Personius 2002).

The extent and character of the unconformity between the Ceja and Arroyo Ojito Formations was not well understood until the Rincones paleosurface was recognized (see below). Connell (2006) correlated reddish-brown deposits beneath Santa Ana Mesa to the Loma Barbon Member (Fig. 2D). Near Loma Barbon, Ceja gravel disconformably overlies reddish-brown sandstone and mudstone of the Loma Barbon Member on the footwall of the Tanaya fault. The Tanaya fault juxtaposes redder and locally coarser conglomeratic deposits of the Santa Ana Mesa Member (east of the Tanaya fault) against somewhat paler (yellowish-brown to yellowish-red) sandstone and pebbly sandstone of the Loma Barbon Member of the Arroyo Ojito Formation, which contains fewer conglomeratic lenses than the Santa Ana Mesa Member.

Although much of the western flank of Santa Ana Mesa is poorly exposed, the southwestern edges of the mesa contain excellent exposures that are the likely location of Soister's stratigraphic section (Fig. 8E). Reexamination of Soister's (1952) type area has not been accomplished to date because requests for access to the western flank of Santa Ana Mesa have not been allowed yet. Although his descriptions are generalized, his choice of the Santa Ana Mesa member to describe a succession of reddish-brown deposits that overlie older rocks of the Santa Fe Group is reasonable and provides a basis for defining a new member of the Ceja Formation.

The Santa Ana Mesa Member is herein redefined for reddish-brown sandstone and conglomerate beneath the basalts on Santa Ana Mesa (Fig. 10). These reddish-brown deposits extend south of Santa Ana Mesa into Rio Rancho and along the eastern edge of the Rio Grande valley. The generalized stratigraphic section of Soister (1952, table IV, pp. 40–42; Appendix D) is designated as a provisional type section with the qualification that the type section along the western flank of Santa Ana Mesa be redescribed when access becomes available. The boundary between the Santa Ana Mesa Member and probable deposits of the Loma Barbon Member (Arroyo Ojito Formation) is provisionally placed at his unit 5–6 contact because the overlying deposits tend to be reddish rather than brownish in color (Appendix D).

The Santa Ana Mesa Member is red and light-reddish-brown to yellowish-red (2.5YR 5/6 and 5YR 6/4-5/6), fine- to coarse-grained, medium- to thickly bedded sandstone and pebbly to cobbly sandstone. Gravels include gray, rounded, rhyodacitic(?) cobbles that weather to form deeply pitted clast surfaces. The Santa Ana Mesa Member contains abundant volcanic and red granitic and gneissic gravel, with subordinate chert and orthoquartzite; sandstone gravel is sparse. Deposits become progressively finer grained toward the Rio Grande valley, where fine- to medium-grained sandstone and mudstone predominate. Soister (1952, pp. 39 and 43) reported interfingering of reddish-brown sediment of the Santa Ana Mesa Member with light-gray silty sandstone exposed along the eastern flank of this mesa. These light-gray sediments are correlated to axial-fluvial deposits of the Sierra Ladrones Formation (Fig. 8F; Cather and Connell 1998). Interfingering relationships between the axial-fluvial deposits of the Sierra Ladrones Formation and the Santa Ana Mesa Member of the Ceja Formation are portrayed on a reference stratigraphic section that was described along the southeastern flank of Santa Ana Mesa (Fig. 10, Appendix E).

The Santa Ana Mesa Member is typically redder than the other members of the Ceja Formation. It is locally coarse grained than the Atrisco Member. The Santa Ana Mesa Member also differs from other members of the Ceja Formation because it contains a greater proportion of volcanic detritus, including conglomeratic lenses containing dacitic and rhyodacitic cobbles. The boundary between the Santa Ana Mesa and Atrisco Members is not clear, but it probably lies between the Ziana anticlinal accommodation zone and the San Ysidro fault (Fig. 4).

Differences in color between the Atrisco and Santa Ana Mesa Members may reflect different source area composition. Yellowish-brown hues and the generally west and southwest distribution of the Atrisco Member suggest derivation from sources in the southeastern Colorado Plateau. The yellowish-red hues, abundant volcanic detritus, and northerly distribution of the Santa Ana Mesa Member suggest derivation from the southern Jemez Mountains and eastern flanks of the Sierra Nacimiento.

Map relationships, expressed by different elevations of the "upper sandstone and conglomerate" (QTsug) and "upper sandstone and siltstone" (Tsus), are interpreted to represent interfingering of the Rio Puerco and Santa Ana Mesa Members, respectively (Loma Machete quadrangle, Personius et al. 2000). The Santa Ana Mesa Member corresponds to the red member of Spiegel (1961), middle red formation of Lambert (1968), Santa Fe Formation of Kelley (1977), and the Ceja and Loma Barbon of Personius (2002).

Rio Puerco Member (new name)

The Rio Puerco Member of the Ceja Formation is named for the Rio Puerco, a major tributary to the Rio Grande that drains the southeastern Colorado Plateau, San Juan Basin, and the western flank of the Sierra Nacimiento (Love and Connell 2005). The Rio Puerco Member forms the mesa-capping gravel exposed along Ceja del Rio Puerco (Fig. 1). The type section of the Rio Puerco Member is defined at El Rincón (Appendix B), where it culminates in a laterally extensive mesa-capping gravelly sand and contains strongly developed petrocalcic soils of the Llano de Albuquerque geomorphic surface (Figs. 8C and 9). The Rio Puerco Member overlies the Atrisco Member and is the highest member of the Ceja Formation. This member contains very pale brown to light-yellowish-brown, thin- to medium-bedded, planar to trough cross-stratified pebble to cobble gravel and pebbly to cobbly sand and fine- to coarse-grained sand, with scattered boulders and large cobbles. Gravel textures appear to be very poorly sorted and contain abundant pebbles and small cobbles, with minor to subordinate small boulders and large cobbles. The Rio Puerco Member contains abundant volcanic gravel with subordinate chert, red granitic, and sedimentary (mostly sandstone) gravel.

The boundary between the Atrisco and Rio Puerco Members is locally sharp and disconformable along the northern Ceja del Rio Puerco and La Ceja. At the El Rincón stratotype, the base is gradational and interfingers with the Atrisco Member. The Atrisco–Rio Puerco Member boundary is placed at the highest, laterally extensive (at least 500 m in lateral extent), thickly bedded mudstone or muddy sandstone. Conglomeratic deposits of the Rio Puerco Member locally overlie the Cerro Conejo Formation west of the Sand Hill fault (Fig. 8B). The Rio Puerco Member disconformably overlies the Loma Barbon Member near Loma Barbon (Fig. 1).

Pantadeleon Formation (abandoned)

Connell et al. (1999) named the Pantadeleon Formation for deposits locally eroded from fault scarps associated with major intrabasinal faults in the northwestern Albuquerque Basin. The Pantadeleon Formation represents a succession of syntectonic deposits that contain many buried soils preserved on the hanging wall of the Zia fault at the head of Arroyo Pantadeleon near La Ceja (Figs. 2D and 6). They considered this unit to represent local, episodic deposition of fluvial and colluvial sediments along the hanging walls of actively subsiding intrabasinal normal faults.

The Pantadeleon Formation disconformably rests on strongly developed petrocalcic soils (paleosols) correlated by Connell et al. (1999) to the Llano de Albuquerque surface. The Pantadeleon Formation (sensu Connell et al. 1999) contains very pale brown to light-yellowish-brown, poorly to moderately sorted sand and gravelly sand. Subsequent geologic mapping on the northwestern part of the basin demonstrates the presence of two strongly developed soils that locally bound the top and base of the Ceja Formation (Fig. 8C).

The texture, color, and stratigraphic

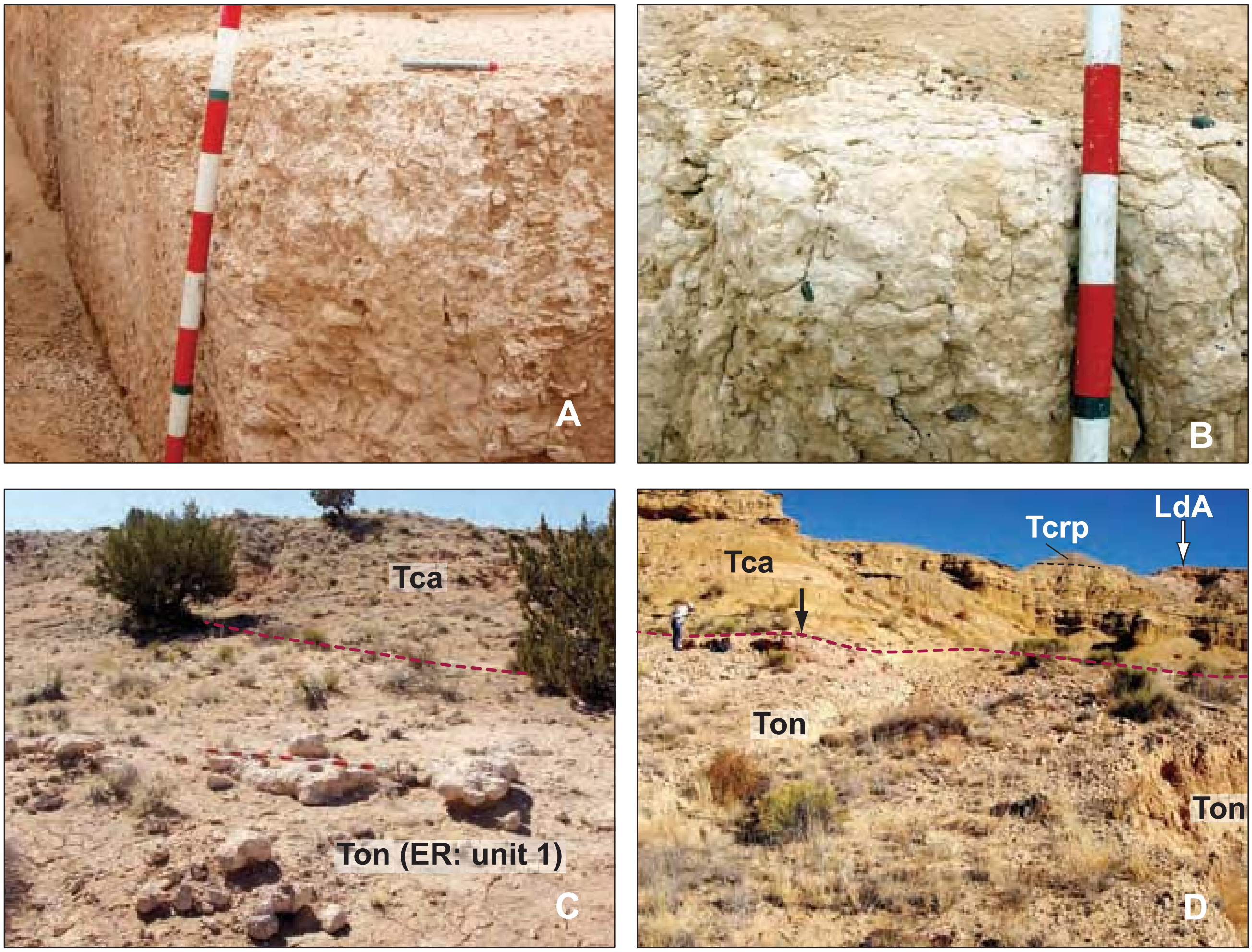


FIGURE 11—Photographs of boundary associated with the Rincones paleosurface. Refer to Figure 3 for approximate locations of photographs. A Jacob staff with decimeter increments is shown in photographs **A–C** for reference. Thick red dashed line denotes the Rincones paleosurface. **A**—Petrocalcic soils of Rincones paleosurface exhibiting stage III+ pedogenic carbonate morphology in a shallow trench. **B**—Petrocalcic soil developed on Navajo Draw Member exhibiting stage III+ pedogenic carbonate morphology exposed along Ceja del Rio Puerco near Bernalillo-Sandoval County line. **C**—Cemented sandstone nodules marking boundary between Ceja Formation (above) and Navajo Draw Member at El Rincón stratotype. **D**—Mudstone and sandstone of the Atrisco Member overlying Navajo Draw Member deposits, just east of hanging wall of Cat Mesa fault.

position of the Pantadeleon Formation (described in Connell et al. 1999) is effectively the same as exposures of the Ceja Formation along the Ceja del Rio Puerco (Fig. 8A–D). The lower part of the Pantadeleon Formation contains multiple paleosols near the footwalls of the San Ysidro and Zia faults. These soils are considered a local record of periodic or episodic faulting (cf. Wright 1946). Although the fault wedges of the Pantadeleon Formation are locally recognized along intrabasinal faults, they are not easily mapped at a regional scale (i.e., 1:24,000 or smaller). The Pantadeleon Formation is similar in composition to the Ceja Formation and occupies the same stratigraphic position. Thus, the Pantadeleon Formation should be abandoned, and these deposits should be included within the Ceja Formation and its constituent members (Fig. 2G).

Rincones paleosurface (new name)

The Rincones paleosurface is informally named for an unconformity between upper Miocene and Pliocene strata. The Rincones paleosurface is named for the Rincones de Zia (Galusha 1966; also called La Ceja, Fig. 1), a north-facing escarpment at the northern edge of the Llano de Albuquerque (Fig. 8A). The name La Ceja is not used for this boundary because it is similar to the lithostratigraphic term Ceja Formation (see above), and adoption of this name would create confusion between this paleosurface and overlying deposits. The Rincones paleosurface was originally miscorrelated to the mesa-capping Llano de Albuquerque surface by Connell et al. (1999). Miscorrelation of soils of the Rincones paleosurface to the Llano de Albuquerque geomorphic surface arose because of generally poor exposure and a northward convergence of these two surfaces, where the intervening Ceja deposits thin to less than 10 m along La Ceja. The Rincones paleosurface is proposed herein because it represents an important mappable feature that differentiates Pliocene from upper Miocene sediments.

The Rincones paleosurface is recognized by a disconformity or a very slight angular unconformity between the Ceja Formation and the subjacent Arroyo Ojito and Cerro Conejo Formations (Fig. 11C–D and Fig. 4). The angular stratal discordance is commonly less than 5° to the southeast and is commonly recognized near intrabasinal faults. Along the Ceja del Rio Puerco, this boundary locally contains petrocalcic soils that exhibit stage III+ pedogenic carbonate morphology developed on the Navajo Draw Member (Fig. 11B). Elsewhere, this boundary is erosional with a 1.5-m-thick pink to pinkish-white (7.5YR 7/4-8/2), fine- to medium-grained, bioturbated sandstone with scattered fine pebbles and irregular-shaped concretions (Fig. 11C–D and Fig. 4). The erosional nature of this contact is recorded by the presence of locally abundant fluvially reworked, white, micritic carbonate nodules within the Ceja Formation in the Rio Rancho area. A petrocalcic soil associated with the Rincones paleosurface is buried to the east near Rio Rancho (Fig. 11A). The base of the Atrisco Member may represent the basinward subsurface extension of the Rincones paleosurface.

At the La Ceja type area, paleosols associated with the Rincones paleosurface are as much as 2.5 m thick and exhibit stage V pedogenic carbonate morphology on the Picuda Peak Member (Fig. 8A; Connell et al. 1999). Paleosols associated with the Rincones paleosurface are weaker on the footwall of the Zia and San Ysidro faults. These soils exhibit stage III+ carbonate morphology and are similar to those developed on the Llano de Albuquerque to the south. Variations in soil-morphologic development indicate that the Rincones paleosurface is likely compound in nature and may represent a number of distinct but related surfaces that demarcate Miocene and Pliocene strata.

The magnitude of erosion that marks the Rincones paleosurface can be estimated by comparing the thickness of stratigraphic units and markers (e.g., Fig. 7). On the footwall of the Sand Hill fault, more than 400 m of the Cerro Conejo and Arroyo Ojito Formations have been removed by erosion. On the footwall of the San Ysidro fault along La Ceja, at least 250 m of the Arroyo Ojito Formation have been eroded. A fault-bounded block between the San Ysidro and Zia faults may represent the structurally lowest and best preserved section, where erosion of the Arroyo Ojito Formation was minimal and paleosols are strongly developed. A bed of 6.8 Ma volcanic fallout lapilli lies approximately 3 m below the Ceja–Loma Barbon contact near Loma Barbon. This vertical juxtaposition indicates the removal of at least 100–150 m of Loma Barbon deposits (relative to the Arroyo Ojito stratotype) along the eastern flank of the Ziana anticlinal accommodation zone.

Discussion

Proposed refinements to the stratigraphic nomenclature of Neogene fluviatile sediments in the northwestern Albuquerque Basin are based largely on the discovery of a stratigraphically important unconformity between upper Miocene and Pliocene sedimentary rocks. The Rincones paleosurface represents an erosional boundary between the Ceja and Arroyo Ojito Formations that resolves important ambiguities in the stratigraphic framework of the Santa Fe Group in the northwestern Albuquerque Basin proposed by Connell et al. (1999). This revised nomenclature (Fig. 2G) should clarify current and future stratigraphic usage (e.g., Connell 2006, in press).

Stratigraphic usage of "middle red formation" (member) of the Santa Fe Group (Formation) has evolved into a generalized term describing reddish-colored sediments exposed in the western Albuquerque Basin. The most noteworthy problem with use of the middle red formation (or member) is that it refers to at least four different reddish-colored units that occupy at least two distinct stratigraphic positions (e.g., Fig. 2A, C, and F). The reddish-brown Atrisco Member and yellowish-red Santa Ana Mesa Member of the Ceja Formation sit above the Rincones paleosurface. The light-reddish-brown Loma Barbon Member and pinkish-gray to reddish-yellow Picuda Peak Member of the Arroyo Ojito Formation underlie this boundary. Recognition of the Rincones paleosurface at the Ceja stratotype requires abandonment of the term Ceja for subjacent deposits described at Arroyo Ojito by Connell et al. (1999). The Picuda Peak Member of the Arroyo Ojito Formation is proposed to resolve a gap in the stratigraphic nomenclature created by this reassignment of the Ceja Formation to deposits overlying the Rincones paleosurface.

The Ceja lithostratigraphic unit contains at least three mappable units and should be elevated to formation rank. The Atrisco and Santa Ana Mesa Members mark the base of the Ceja Formation. These deposits are generally finer grained than the overlying gravel-dominated Rio Puerco Member. Geological reconnaissance work south of the study area suggests that at least two more member-rank units may be required to fully describe the Ceja Formation in the southern part of the Albuquerque Basin (e.g., Love et al. 2001, pp. 33–34 and pp. 42–43). This proposed change in rank for the Ceja is in general agreement with the Albuquerque quadrangle compilation of Williams and Cole (2005, 2007); however, they placed the lower boundary of their Ceja Formation (unit Tc/Tmb contact, Fig. 9) at the Atrisco–Rio Puerco Member contact along the Ceja del Rio Puerco of Connell (2006, in press). The basal Ceja Formation boundary of Williams and Cole (2005, 2007) is locally scoured and sits more than 46 m above the Rincones paleosurface (Fig. 9).

Bryan and McCann (1938) proposed the existence of a regional unconformity that separates subhorizontally stratified deposits and underlying deformed strata. They referred to this boundary as the Ortiz surface, after a conoplain described by Oglivie (1905) along the flanks of the Ortiz Mountains (Figs. 1, 6). Spiegel and Baldwin (1963) considered the Ortiz surface to be compound, representing a sequence of erosion and deposition, followed by erosion. They divided the Ortiz into a lower (erosional) paleosurface from an upper (aggradational) surface. Kelley (1977) extended the Ortiz surface throughout the Albuquerque Basin; however, he applied this term to a number of low-relief surfaces that have subsequently been shown to have different ages and degrees of soil development (e.g., Machette 1985). The top of the Ceja Formation was considered part of a regional erosional surface known as the Ortiz surface (Bryan and McCann 1938; Kelley 1977); however, Machette (1985) demonstrated that the Llano de Albuquerque is actually a pedogenically modified remnant of an abandoned depositional surface on the Santa Fe Group. Bachman and Mehnert (1978) restricted the Ortiz surface to a single upper aggradational surface. C. E. Stearns (1979) considered the distinction between upper and lower surfaces to be unnecessary and undesirable because it is the lower paleosurface that defines an important deformational and erosional interval in the history of the Rio Grande rift.

The Rincones paleosurface represents an important Miocene–Pliocene unconformity that may be traceable across the Albuquerque Basin. It is a reasonable correlative to the (lower) Ortiz paleosurface and may represent an important tectonostratigraphic boundary throughout the Rio Grande rift in New Mexico. This paleosurface is likely correlative to other angular unconformities recognized between subhorizontally bedded Pliocene–Pleistocene deposits that overlie slightly or moderately dipping Miocene strata in other basins of the Rio Grande rift. These other (typically angular) unconformities include the Palomas–Rincon Valley contact in southern New Mexico (e.g., Mack et al. 2006), the Sierra Ladrones–Popotosa contact in central New Mexico (Cather et al. 1994), and the Ancha–Tesuque contact in northern New Mexico (Koning et al. 2002). These stratigraphic lacunae span the Miocene–Pliocene boundary, which represents an important event in the evolution of the Albuquerque Basin, when the ancestral Rio Grande flowed through rift basins of central and southern New Mexico (Connell et al. 2005).

If the Rincones paleosurface represents a regionally important tectonostratigraphic boundary, then additional age constraints on younger deposits, such as the Ceja Formation, can be inferred. For example, Machette (1978) delineated a Pliocene volcanic center called the Basalt at San Acacia. This volcanic feature, which is less than 60 km south of the study area, lies within the lower Sierra Ladrones Formation (Machette 1978). The Sierra Ladrones Formation disconformably overlies tilted strata of the Popotosa Formation. The Sierra Ladrones–Popotosa contact may represent a correlative boundary to the Rincones paleosurface (see above). A sample from this volcanic feature yielded a whole-rock $^{40}Ar/^{39}Ar$ age of 4.87 ± 0.04 Ma (R. M. Chamberlin and W. C. McIntosh, unpubl. data; cf. K-Ar age of 4.5 ± 0.1 Ma by Bachman and Mehnert 1978). Thus, if the Rincones paleosurface and Sierra Ladrones–Popotosa boundary are generally correlative, deposition of the Ceja Formation may extend into early Pliocene time.

The abandonment of the Pantadeleon Formation demonstrates how new geologic mapping leads to the continued evolution of stratigraphic nomenclature in geologic basins. Discovery of the Rincones paleosurface resolves important, but heretofore ambiguous, stratigraphic relationships, clarifying and simplifying the stratigraphic nomenclature refined herein. A new lithostratigraphic term to describe localized deposition into depressions formed adjacent to intrabasinal fault scarps (encapsulated by the Pantadeleon Formation of Connell et al. 1999) would be useful, but a replacement term is not proposed here.

Conclusions

Recent compilations of the geology of the Albuquerque–Rio Rancho metropolitan area and vicinity treat the stratigraphy of the Santa Fe Group in the northwestern Albuquerque Basin differently (Williams and Cole 2005, 2007; Connell 2006, in press; Maldonado et al. 2007). This varying treatment of the stratigraphy was due to a lack of consensus on a regionally consistent stratigraphic nomenclature during mapping of the constituent (7.5-min) geologic quadrangles. Key stratigraphic relationships were not fully understood until after these quadrangles were completed. The discovery of a stratigraphically important unconformity called the Rincones paleosurface clarifies some of the ambiguity in stratigraphic usage in the region and allows for the creation of a regionally consistent nomenclature for the northwestern part of the Albuquerque Basin.

This paper proposes refinements to the stratigraphic nomenclature of Miocene and Pliocene deposits in the northwestern Albuquerque Basin (Figs. 2 and 6). The following revisions are proposed here. The Cerro Conejo is elevated to formation rank. The Ceja is elevated to formation rank and is divided into the Atrisco, Santa Ana Mesa, and Rio Puerco Members. The Pantadeleon Formation is similar to the Ceja Formation and should be abandoned. The Rincones paleosurface may represent an important boundary separating slightly tilted upper Miocene sediments of the Arroyo Ojito Formation from overlying, weakly consolidated and subhorizontally stratified deposits of the Pliocene Ceja Formation. This paleosurface may represent a regionally important tectonostratigraphic boundary separating upper Miocene and Pliocene strata in the Rio Grande rift in New Mexico. The refinements proposed in this paper should facilitate stratigraphic correlations within and among basins of the Rio Grande in New Mexico, and aid in the interpretation of geologic compilations of the Albuquerque Basin (Table 1, Fig. 3), including those of Connell (2006, in press), Williams and Cole (2005, 2007) and Maldonado et al. (2007).

Acknowledgments

This study was supported by the New Mexico Bureau of Geology and Mineral Resources (Dr. Peter Scholle, Director) and the New Mexico STATEMAP Program (Dr. Michael Timmons, Program Manager) of the National Cooperative Geologic Mapping Program of 1992. The revisions proposed in this paper were initially developed during compilation of geologic maps of the region by the author. Nathalie Brandes, Patricia Jackson-Paul, Dan Koning, Dave Love, Dave McCraw, Florian Maldonado, and Steve Rogers assisted in field descriptions of stratigraphic units that led to the units defined in this paper. Jane Ann Bode provided aerial transportation. This paper benefited from sometimes-lively discussions with Steve Barghoorn, Steve Cather, James C. Cole, John Hawley, Dan Koning, Dave Love, Steve Personius, Byron Stone, and Richard Tedford. I am grateful to the Pueblo of Zia, Pueblo of Isleta, and Pueblo of San Felipe for access to tribal lands. I particularly thank Mr. Peter Pino and Mr. John Sorrell for facilitating access to tribal lands. I am also grateful to Ivan Benavidez, the King Brothers ranch, Westland Corporation, Albuquerque Academy, and the city of Rio Rancho for property access. John Hawley, Dan Koning, David Love, Spencer Lucas, and Gary Smith provided constructive reviews.

References

Allen, B. D., Connell, S. D., Hawley, J. W., and Stone, B. D., 1998, Core drilling provides information about Santa Fe Group aquifer system beneath Albuquerque's West Mesa: New Mexico Geology, v. 20, no. 1, pp. 8–13.

Bachman, G. O., and Mehnert, H. H., 1978, New K-Ar dates and the late Pliocene to Holocene geomorphic history of the central Rio Grande region, New Mexico: Geological Society of America, Bulletin, v. 89, pp. 283–292.

Beckner, J. R., and Mozley, P. S., 1998, Origin and spatial distribution of early vadose and phreatic calcite cements in the Zia Formation, Albuquerque Basin, New Mexico, USA; *in* Morad, S. (ed.), Carbonate cementation in sandstones—distribution patterns and geochemical evolution: International Association of Sedimentologists, Special Publication 26, pp. 27–51.

Birkeland, P. W., 1999, Soils and geomorphology: Oxford University Press, New York, 3rd edition, 430 pp.

Brandes, N. N., 2002, Lithostratigraphy and petrography of upper Santa Fe Group deposits in the northern Albuquerque Basin, New Mexico: Unpublished M.S. thesis, New Mexico Institute of Mining and Technology, Socorro, 208 pp.

Bryan, K., and McCann, F. T., 1937, The Ceja del Rio Puerco—a border feature of the Basin and Range province in New Mexico, part I, stratigraphy and structure: Journal of Geology, v. 46, pp. 801–828.

Bryan, K., and McCann, F. T., 1938, The Ceja del Rio Puerco—a border feature of the Basin and Range province in New Mexico, part II, geomorphology: Journal of Geology, v. 46, pp. 1–16.

Cather, S. M., and Connell, S. D., 1998, Preliminary geologic map of the San Felipe Pueblo 7.5' quadrangle, Sandoval County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open-file Geologic Map 19, scale 1:24,000, revised May 2004, online at http://geoinfo.nmt.edu/publications/maps/geologic/ofgm/19/home.html.

Cather, S. M., Chamberlin, R. M., Chapin, C. E., and McIntosh, W. C., 1994, Stratigraphic consequences of episodic extension in the Lemitar Mountains, central Rio Grande rift: Geological Society of America, Special Paper 291, pp. 157–170.

Chamberlin, R. W., Pazzaglia, F. J., Wegmann, K. W., and Smith, G. A., 1999, Preliminary geologic map of Loma Creston 7.5-min quadrangle, Sandoval County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open-file Geologic Map 25, 19 pp., scale 1:24,000, online at http://geoinfo.nmt.edu/publications/maps/geologic/ofgm/25/home.html.

Chapin, C. E., and Cather, S. M., 1994, Tectonic setting of the axial basins of the northern and central Rio Grande rift: Geological Society of America, Special Paper 291, pp. 5–25.

Cole, J. C., Mahan, S. A., Stone, B. D., and Shroba, R. R., 2007, Ages of Quaternary Rio Grande terrace-fill deposits, Albuquerque area, New Mexico: New Mexico Geology, v. 29, no. 4, pp. 123–132.

Compton, R. R., 1985, Geology in the field: John Wiley and Sons, New York, 398 pp.

Connell, S. D., 1998, Geology of the Bernalillo and Placitas quadrangles, Sandoval County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open-file Geologic Maps 2 and 16, scale 1:24,000, revised July 2000, online at http://geoinfo.nmt.edu/publications/maps/geologic/ofgm/2/home.html.

Connell, S. D., 2004, Geology of the Albuquerque Basin and tectonic development of the Rio Grande rift in north-central New Mexico; *in* Mack, G. H., and Giles, K. A. (eds.), The geology of New Mexico—a geologic history: New Mexico Geological Society, Special Publication 11, pp. 359–388.

Connell, S. D., 2006, Preliminary geologic map of the Albuquerque–Rio Rancho metropolitan area and vicinity, Bernalillo and Sandoval Counties, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Report 496, version 2.0, November 2006, scale 1:50,000, CD-Rom and online at http://geoinfo.nmt.edu/publications/openfile/496.

Connell, S. D., in press, Geologic map of the Albuquerque–Rio Rancho metropolitan area and vicinity, Bernalillo and Sandoval Counties, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Geologic Map 78, scale 1:50,000, 2 sheets.

Connell, S. D., and Smith, G. A., 2005, Post-Miocene stratigraphy of the Albuquerque Basin, Rio Grande rift, New Mexico: Implications for geomorphic and hydrogeologic development of extensional basins (abs.): Geological Society of America, Abstracts with programs, v. 37, no. 7, p. 496.

Connell, S. D., Allen, B.D., and Hawley, J. W., 1998, Subsurface stratigraphy of the Santa Fe Group from borehole geophysical logs, Albuquerque area, New Mexico: New Mexico Geology, v. 20, no. 1, pp. 2–7.

Connell, S. D., Hawley, J. W., and Love D. W., 2005, Late Cenozoic drainage development in the southeastern Basin and Range of New Mexico, southeasternmost Arizona, and western Texas; *in* Lucas, S. G., Morgan, G. S., and Ziegler, K. E. (eds.), New Mexico's ice ages: New Mexico Museum of Natural History and Science, Bulletin 28, pp. 125–150.

Connell, S. D., Koning, D. J., and Cather, S. M., 1999, Revisions to the stratigraphic nomenclature of the Santa Fe Group, northwestern Albuquerque Basin, New Mexico; *in* Pazzaglia, F. J., and Lucas, S. G. (eds.), Albuquerque geology: New Mexico Geological Society, Guidebook 50, pp. 337–353.

Connell, S. D., Love, D. W., and Dunbar, N. W., 2007a, Geomorphology and stratigraphy of inset fluvial deposits along the Rio Grande valley in the central Albuquerque Basin, New Mexico: New Mexico Geology, v. 29, no. 1, pp. 13–31.

Connell, S. D., Koning, D. J., Kelley, S. A., and Brandes, N. N., 2007b, Oligocene and early Miocene sedimentation in the southwestern Jemez Mountains and northwestern Albuquerque Basin, New Mexico; *in* Kues, B. S., Kelley, S. A., and Lueth, V. W. (eds.), Geology of the Jemez region II: New Mexico Geological Society, Guidebook 58. pp. 195–208.

Connell, S. D., Love, D. W., Maldonado, F., Jackson, P. B., McIntosh, W. C., and Eppes, M. C., 2000, Is the top of the Santa Fe Group diachronous in the Albuquerque Basin? (abs.); *in* Cole, J. C. (ed.), U.S. Geological Survey Middle Rio Grande Basin

Study—Proceedings of the Fourth Annual Workshop, Albuquerque, New Mexico, February 15–16, 2000: U.S. Geological Survey, Open-file Report 00-488, pp. 18–20.

Connell, S. D., Love, D. W., Cather, S. M., Smith, G. A., Lucas, S. G., 2001, Tectonics, climate, and the transition from aggradation to incision of the upper Santa Fe Group, Albuquerque Basin, central New Mexico (abs.): Geological Society of America, Abstracts with Programs, v. 33, no. 5, p. A-48.

Dutro, J. T., Dietrich, R. V., and Foose, R. M., compilers, 1989, Data sheets: Virginia, American Geological Institute, unpaginated.

Galusha, T., 1966, The Zia Sand Formation, new early to medial Miocene beds in New Mexico: American Museum Novitates, no. 2271, 12 pp.

Galusha, T., and Blick, J. C., 1971, Stratigraphy of the Santa Fe Group, New Mexico: American Natural History Museum, Bulletin, v. 144, 127 pp., 1 pl.

Gawne, C., 1981, Sedimentology and stratigraphy of the Miocene Zia Sand of New Mexico, summary: Geological Society of America, Bulletin, Part I, v. 92, no. 12, pp. 999–1007.

GEOLEX (National Geologic Map Database), 2007, U.S. Geological Survey, http://ngmdb.usgs.gov/Geolex/geolex_home.html, accessed December 15, 2007.

Gile, L. H., Hawley, J. W., and Grossman, R. B., 1981, Soils and geomorphology in the Basin and Range area of southern New Mexico—guidebook to the Desert Project: New Mexico Bureau of Mines and Mineral Resources, Memoir 39, 222 pp.

Hawley, J. W., editor, 1978, Guidebook to Rio Grande rift in New Mexico and Colorado: New Mexico Bureau of Mines and Mineral Resources, Circular 163, 241 pp.

Hawley, J. W., Haase, C. S., Lozinsky, R. P., 1995, An underground view of the Albuquerque Basin: New Mexico Water Resources Research Institute, Report 290, pp. 27–55.

Kelley, V. C., 1977, Geology of Albuquerque Basin, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 33, 60 pp.

Kelley, V. C., and Kudo, A. M., 1978, Volcanoes and related basalts of Albuquerque Basin, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Circular 156, 30 pp.

Koning, D. J., and Personius, S. F., 2002, Preliminary geologic map of the Bernalillo NW quadrangle, Sandoval County: U.S. Geological Survey, Miscellaneous Field Studies Map MF-2404, scale 1:24,000.

Koning, D. J., Connell, S. D., Pazzaglia, F. J., and McIntosh, W. C., 2002, Redefinition of the Ancha Formation and Pliocene–Pleistocene deposition in the Santa Fe embayment, north-central New Mexico: New Mexico Geology, v. 24, no. 3, pp. 75–87.

Koning, D. J., Pederson, J., Pazzaglia, F. J., and Cather, S .M., 1998, Geology of the Cerro Conejo (Sky Village NE) 7.5-minute quadrangle: New Mexico Bureau of Mines and Mineral Resources, Open-file Geologic Map 45, scale 1:24,000, online at http://geoinfo.nmt.edu/publications/maps/geologic/ofgm/45/home.html.

Lambert, P. W., 1968, Quaternary stratigraphy of the Albuquerque area, New Mexico: Unpublished Ph.D. dissertation, University of New Mexico, 329 pp.

Love, D. W., and Connell, S. D., 2005, Late Neogene drainage developments on the southeastern Colorado Plateau, New Mexico; *in* Lucas, S. G., Morgan, G. S., and Ziegler, K. E. (eds.), New Mexico's ice ages: New Mexico Museum of Natural History and Science, Bulletin 28, pp. 151–169.

Love, D. W., Connell, S. D., Lucas, S. G., Morgan, G. S., Derrick, N. N., Jackson-Paul, P. B., and Chamberlin, R., 2001, Third-day, Belen sub-basin—Belen, Sevilleta National Wildlife Refuge, and northern Socorro Basin; *in* Connell, S. D., Love, D. W., Lucas, S. G., Koning, D. J., Derrick, N. N., Maynard, S. R., Morgan, G. S., Jackson-Paul, P. B., and Chamberlin , R. M. (eds.), Stratigraphy and tectonic development of the Albuquerque Basin, central Rio Grande rift, premeeting field-trip guidebook for the Geological Society of America, Rocky Mountain–South Central Section Meeting: New Mexico Bureau of Geology and Mineral Resources, Open-file Report 454A, pp. 27–53.

Lucas, S. G., Williamson, T. E., and Sobus, J., 1993, Plio-Pleistocene stratigraphy, paleoecology, and mammalian biochronology, Tijeras Arroyo, Albuquerque area, New Mexico: New Mexico Geology, v. 15, no. 1, pp. 1–8.

Luedke, R. G., and Smith, R. L., 1978, Map showing distribution, composition, and age of late Cenozoic volcanic centers in Arizona and New Mexico: U.S. Geological Survey, Miscellaneous Investigations Series, I-1091-A, scale 1:1,000,000.

Machette, M. N., 1978, Geologic map of the San Acacia quadrangle, Socorro County, New Mexico: U.S. Geological Survey, Geologic Quadrangle Map, GQ-1415, scale 1:24,000.

Machette, M. N., 1985, Calcic soils of the southwestern United States: Geological Society of America, Special Paper 203, pp. 1–42.

Machette, M. N., Long, T., Bachman, G. O., and Timbel, N. R., 1997, Laboratory data for calcic soils in central New Mexico—background information for mapping Quaternary deposits in the Albuquerque Basin: New Mexico Bureau of Mines and Mineral Resources, Circular 205, 63 pp.

Mack, G. H., Seager, W. R., Leeder, M. R., Perea-Arlucea, M., and Salyards, S. L., 2006, Pliocene and Quaternary history of the Rio Grande, the axial river of the southern Rio Grande rift, New Mexico, USA: Earth-Science Reviews, v. 79, pp. 141–162.

Maldonado, F., Budahn, J. R., Peters, L., and Unruh, D. M., 2006, Geology, geochronology, and geochemistry of basaltic flows of the Cat Hills, Cat Mesa, Wind Mesa, Cerro Verde, and Mesita Negra, central New Mexico: Canadian Journal of Earth Sciences, v. 43, no. 9, pp. 1251–1268.

Maldonado, F., Slate, J. L., Love, D. W., Connell, S. D., Cole, J. C., and Karlstrom, K. E., 2007, Geologic map of the Pueblo of Isleta tribal lands and vicinity, Bernalillo, Torrance, and Valencia Counties, central New Mexico: U.S. Geological Survey, Scientific Investigations Map 2913, 35 pp., 1 sheet, scale 1:50,000.

Morgan, G. S., and Lucas, S. G., 2003, Mammalian biochronology of Blancan and Irvingtonian (Pliocene and early Pleistocene) faunas from New Mexico: American Museum of Natural History, Bulletin, v. 13, no. 279, pp. 269–320.

Morgan, G. S., and Williamson, T. E., 2000, Middle Miocene (late Barstovian) vertebrates from the Benavidez Ranch local fauna, Albuquerque Basin, New Mexico; *in* Lucas, S. G. (ed.), New Mexico's fossil record 2: New Mexico Museum of Natural History and Science, Bulletin 16, pp. 195–207.

Munsell Company, 1992, Soil color chart: Munsell Company, Kollmorgen Instruments Corporation, New York.

North American Commission on Stratigraphic Nomenclature (NACSN), 2005, North American Stratigraphic Code: American Association of Petroleum Geologists, Bulletin, v. 89, no. 11, pp. 1547–1591.

Ogilvie, I. H., 1905, The high-altitude conoplain: a topographic form illustrated in the Ortiz Mountains: American Geologist, v. 36, pp. 27–34.

Personius, S. J., 2002, Geologic map of the Santa Ana Pueblo quadrangle, Sandoval County, New Mexico: U.S. Geological Survey, Miscellaneous Field Studies Map, MF-2405, scale 1:24,000.

Personius, S. F., Machette, M. N., and Stone, B. D., 2000, Preliminary geologic map of the Loma Machete quadrangle, Sandoval County, New Mexico: U.S. Geological Survey, Miscellaneous Field Investigations, MF-2334, scale 1:24,000, version 1.0.

Shroba, R. R., Thompson, R. A., Schmidt, D. L., Personius, S. F, 2003, Geologic map of the La Mesita Negra SE quadrangle, Bernalillo County, New Mexico: U.S. Geological Survey, Miscellaneous Field Studies Map, MF-2416, scale 1:24,000.

Smith, G. A., McIntosh, W. C., and Kuhle, A. J., 2001, Sedimentologic and geomorphic evidence for seesaw subsidence of the Santo Domingo accommodation-zone basin, Rio Grande rift, New Mexico: Geological Society of America, Bulletin, v. 113, no. 5, pp. 561–574.

Soister, P. E., 1952, Geology of Santa Ana Mesa and adjoining areas, Sandoval County, New Mexico: Unpublished M.S. thesis, University of New Mexico, 126 pp.

Spiegel, Z., 1961, Late Cenozoic sediments of the lower Jemez River region; *in* Northrop, S. A. (ed.), Albuquerque country: New Mexico Geological Society, Guidebook 12, pp. 132–138.

Spiegel, Z., and Baldwin, B., 1963, Geology and water resources of the Santa Fe area, New Mexico: U.S. Geological Survey, Water-Supply Paper 1525, 258 pp.

Stearns, C. E., 1979, New K-Ar dates and the late Pliocene to Holocene geomorphic history of the central Rio Grande region, New Mexico: Discussion: Geological Society of America, Bulletin, v. 90, no. 8, pp. 799–800.

Stone, B. D., Allen, B. D., Mikolas, M., Hawley, J. W., Haneberg, W. C., Johnson, P. S., Allred, B., and Thorn, C. R., 1998, Preliminary lithostratigraphy, interpreted geophysical logs, and hydrogeologic characteristics of the 98th Street core hole, Albuquerque, New Mexico: U.S. Geological Survey, Open-file Report 98-0210, 82 pp.

Tedford, R. H., and Barghoorn, S., 1997, Miocene mammals of the Española and Albuquerque basins, north-central New Mexico; *in* Lucas, S. G., Estep, J. W., Williamson, T. E., and Morgan, G. S. (eds.), New Mexico's fossil record 1: New Mexico Museum of Natural History and Science, Bulletin 11, pp. 77–95.

Tedford, R. H., and Barghoorn, S., 1999, Santa Fe Group (Neogene), Ceja del Rio Puerco, northwestern Albuquerque Basin, Sandoval County, New Mexico; *in* Pazzaglia, F. J., and Lucas, S. G. (eds.), Albuquerque geology: New Mexico Geological Society, Guidebook 50, pp. 327–335.

Tedford, R. H., Albright, L. B., III, Barnosky, A. D., Ferrusquia-Villafranca, I., Hunt, R. M., Jr., Storer, J. E., Swisher, C. C., III, Voorhies, M. R., Webb, S. D., and Whistler, D. P., 2004, Mammalian biochronology of the Arikareean through Hemphillian interval (late Oligocene through early Pleistocene epochs); *in* Woodburne, M. O. (ed.), Late Cretaceous and Cenozoic mammals of North America: biostratigraphy and geochronology: Columbia University Press, New York, pp. 169–231.

TS-Creator, 2007, TS-Creator visualization of enhanced Geologic Time Scale 2004 database: James Ogg (database coordinator) and Adam Lugowski (software developer), version 3.0, http://www.stratigraphy.org and http://www.chronos.org

Williams, P. L., and Cole, J. C., 2005, Preliminary geologic map of the Albuquerque 30′ x 60′ quadrangle, north-central New Mexico: U.S. Geological Survey, Open-file report 2005-1418, 52 pp., 1 map, scale 1:100,000.

Williams, P. L., and Cole, J. C., 2007, Geologic map of the Albuquerque 30′ x 60′ quadrangle, north-central New Mexico: U.S. Geological Survey, Scientific Investigations Map 2946, 31 pp., scale 1:100,000.

Wright, H. E., 1946, Tertiary and Quaternary geology of the lower Rio Puerco area, New Mexico: Geological Society of America, Bulletin, v. 57, no. 5, pp. 383–456.

Appendices

Colors measured dry notation, where available using Munsell (1992). Textural abbreviations for sand include: very fine, vfL, vfU; fine, fL, fU; medium, mL, mU; coarse, cL, cU; and very coarse, vcL, vcU. Pedogenic carbonate morphologic stages from Birkeland (1999). Measured upsection with Abney level and Jacob staff. Numerical unit designations established upsection, and listed in descending stratigraphic order. Locations given using Universal Transverse Mercator (UTM) coordinates (zone 013S, NAD 83).

Appendix A

Upper part of Marillo and Zia stratigraphic sections of Brandes (2002, units 15–19) and designated herein as the type section of the Picuda Peak Member of the Arroyo Ojito Formation (**MZ**, Fig. 7). Top of measured section near E: 341,510 m; N: 3,920,520 m, Bernalillo NW 7.5-min quadrangle, Sandoval County.

Unit	Description	Thickness (m)
Arroyo Ojito Formation, Picuda Peak Member (Top, 51 m)		
19.	Interbedded sandstone and mudstone; reddish-yellow very fine to coarse-grained (vfU to cU), moderately sorted sandstone with subangular to rounded grains; beds as much as 70 cm thick with internal planar laminations; mudstone beds are as much as 30 cm thick and weather in blocks. Section ends at top of ridge on degraded remnants of a petrocalcic soil with stage IV pedogenic carbonate morphology.	17.9
18.	Conglomerate; discontinuous lenses of pebble to cobble conglomerate, subangular to rounded clasts of granite, chert, and volcanic rocks; planar bedding.	4.5
17.	Interbedded sandstone and mudstone; very fine to medium-grained (vfU-mU), moderately sorted sandstone with subrounded to rounded grains that form beds as much as 50 cm thick with internal planar laminations. Mudstone beds are as much as 30 cm thick and weather to a blocky texture.	17.5
16.	Interbedded sandstone and conglomerate; reddish-yellow (7.5YR 6/6) sandstone and conglomerate; conglomeratic beds as much as 1 m thick and contain subangular to rounded granite, volcanic, and chert pebbles and cobbles; conglomerates are planar bedded with undulatory bases. Sandstone is fine to coarse grained (fL to cU) and moderately sorted with subangular to subrounded grains; sandstone beds are as much as 1 m thick and have planar to cross-laminations.	10.7
Arroyo Ojito Formation, Loma Barbon Member (Tob, 134 m)		
15.	Sandstone; very pale brown (10YR 7/4), vfU to mL, moderately sorted, subangular to subrounded, planar to low-angle cross-laminations. Loma Barbon Member continues downsection to unit of Zia stratigraphic section of Brandes (2002).	7.5

Appendix B

Revised and extended type section of the Ceja Formation (**ER**, Fig. 9) at Lambert's (1968) El Rincón stratigraphic section (La Mesita Negra and La Mesita Negra SE quadrangles, Bernalillo County, New Mexico. El Rincón section of Lambert (1968, pp. 271–274) and Kelley (1977, table 8, p. 20). Measured and described by S. D. Connell. Overlain by 10 m of reddish- to yellowish-brown, fine-grained eolian sand (not described). Top of section at E: 329,425 m; N: 3,884,250 m; Base of section at E: 327,394 m; N: 3,882,052 m. Unit 2/1 boundary at E: 328,376 m; N: 3,883,983 m; unit 4/3 boundary at E: 328,805 m; N: 3,884,225 m.

Unit	Description	Thickness (m)
Ceja Formation, Rio Puerco Member (Tcrp, 35 m)		
9.	Sandstone; petrocalcic soils of Llano de Albuquerque surface exhibit stage III+ pedogenic carbonate morphology; upper soil is approximately 2 m thick; highly bioturbated below petrocalcic horizons; buried by eolian sand dunes; unit R6 of Lambert (1968).	3.0
8.	Cobbly sand; light-yellowish-brown to reddish-yellow (7.5YR 6/6 to 10YR 7/4), cobbly to pebbly sand; gravels are mostly clast supported; matrix is fine- to coarse-grained cross-laminated sandstone; gravels commonly imbricated indicating southerly transport direction; contains zones of pinkish-white (7.5YR 8/2) calcium-carbonate nodules and mottles indicating bioturbation; unit R6 of Lambert (1968).	32.2
Ceja Formation, Atrisco Member (Tca, 61–63 m)		
7.	Sand, fine- to coarse-grained, medium- to thick-bedded, bioturbated, cross-stratified sandstone; unit R5 of Lambert (1968).	11.0
6.	Sand and pebbly sand; pink (7.5YR 7/4), fine- to coarse-grained sandstone with medium- to thickly bedded pebbly and cobbly sandstone interbeds; contains upward-fining sequences consisting of basalt pebble to cobble gravel that grades upward into pebbly to cobbly sand; units R3–5 of Lambert (1968).	16.0
5.	Clay; light-reddish-brown (5YR 6/4), thinly laminated, slightly calcareous, plastic clay with thin, lenticular sandstone interbeds; unit R2 of Lambert (1968).	3.5
4.	Sandstone; reddish-yellow (7.5YR 7/6), very fine grained, well-sorted sandstone with medium-bedded, red (2.5YR 4/6) claystone interbeds; sandstone contains horizons of calcium-carbonate nodules and weakly developed calcic soils exhibiting stage II pedogenic carbonate morphology; unit R1 of Lambert (1968).	15.2
3.	Sandstone; very poorly exposed; similar to unit 2; unit R1 of Lambert (1968).	~6
2.	Sandstone; pink (7.5YR 7/3), fine- to medium-grained, well-sorted, medium-bedded and locally planar cross-laminated sandstone; locally contains massive mottled beds interpreted as bioturbated zones; interbedded thin- to thickly bedded, brown (7.5YR 4/4) to yellowish-red (5YR 5/6) mudstone. Lower 9–11 m is very poorly exposed at southern edge of El Rincón.	9–11

Arroyo Ojito Formation, Navajo Draw Member (Ton)		
1.	Sandstone; light-yellowish-brown (10YR 6/4), well-sorted, medium-grained tabular sandstone with light-yellowish-brown (2.5Y 6/3) to light-brown (7.5YR 6/3), thinly to medium-bedded mudstone interbeds and scattered well-cemented pebbly sandstone and coarser sandstone lenses; gravel contains fine pebbles of rounded chert and gray volcanic tuff with sparse granite and orthoquartzite; top locally marked by 10–20-cm-thick cemented bed; forms poorly exposed slopes; overlying units tend to form slightly steeper and better exposed slopes. Base of Cerro Colorado dacite projected approximately 43–55 m below Navajo Draw Member and Ceja Formation contact.	14.0

Appendix C

Measured section of Ceja reference section at Cat Mesa, Rio Puerco 7.5-min quadrangle (**CM**, Fig. 9). Top of unit 0 at E: 321,535 m; N: 3,858,635 m. Units C–5 measured upsection from unit C by S.D. Connell on November 30, 1999, with assistance from D.W. Love and F. Maldonado.

Unit	Description	Thickness (m)
Ceja Formation, Rio Puerco Member (Tcrp, 13 m)		
5.	Sand; white to reddish-yellow (N8/0 to 7.5YR 6/6), moderately sorted, fine- to medium-grained sand; strongly developed soil with degraded stage III+ carbonate morphology at top of unit. Pebbles are generally absent or compose <5% of unit.	3.3
4.	Pebbly sand; very pale brown (10YR 7/4 and 8/4), poorly sorted, very fine to very coarse grained (silt-vcU), matrix-supported pebbly sand; 20–40% gravel. Gravel size distribution is generally bimodal, containing mostly subrounded to subangular fine pebbles as much as 3 cm in diameter with scattered (<15%) 10-cm-diameter clasts. Unit is consolidated but not generally cemented by calcium carbonate. Forms slope at top of section. Medium- to thickly bedded, lenticular, moderately sorted, fine- to medium-grained (fL-mU) sand lens.	3.4
3.	Silty sand; pale-brown (10YR 6/3), poorly sorted, fine-grained (mostly fU) silty sand. Grades upsection to pink (7.5YR 7/3-7/4) silty sand with scattered pebbles (<5%) and cylindrical calcium-carbonate nodules. Matrix is slightly cemented with calcium carbonate.	2.8
2.	Pebbly sand and sand; light-brownish-gray (10YR 6/2), poorly sorted, coarse-grained (vfL-cL), cross-stratified, medium- to very thickly bedded, matrix- and clast-supported pebbly sand, pebble gravel (15–45% gravel), and sand. Gravel composed of fine- to medium-diameter, rounded to subangular pebbles with scattered subangular cobbles of Cat Mesa basalt as much as 15 cm in diameter. Clast size distribution is bimodal with abundant fine pebbles as much as 3 cm in diameter and scattered pebbles as much as 15 cm in diameter. Moderately consolidated but not cemented with calcium carbonate. Basal 30 cm contains local pebble and cobble gravel that forms sharp, scoured contact with unit 1.	3.2
Ceja Formation, Atrisco Member (Tca, 6 m)		
1.	Silty sand and clay; reddish-yellow (7.5YR 7/6), well-sorted, massive to tabular, thickly bedded, fine-grained (fL) sand with interbedded light-yellowish-brown (10YR 6/4 to 2.5Y 6/4), silty clay with selenite crystals as much as 1 cm long. Base of clay is sharp; upper contact is gradational with sand. Sand contains little or no calcium-carbonate cement; clay contains calcium carbonate. Sand contains scattered, hard carbonate nodules as much as 4 cm in diameter.	6.0
0.	Basaltic lava flow on Cat Mesa; dark-gray to grayish-black (N3/0-N2/0), coarse-grained, locally vesiculated, porphyritic basaltic flow with dyktytaxitic texture. Groundmass is coarsely microgranular and composed of plagioclase, olivine, clinopyroxene, magnetite(?), and ilmenite(?). Groundmass dated at 3.00 ± 0.01 Ma using $^{40}Ar/^{39}Ar$ method (locality 10, table 1, Maldonado et al. 2006).	2.0
Arroyo Ojito Formation, Navajo Draw Member (Ton, >18 m)		
B.	Silty sand; upper 35 cm to upper contact with Cat Mesa basalt (unit 0) is very pale brown (10YR 6/4), very poorly sorted sand with cinders, rounded fine pebbles, and subangular pebbles of cemented Santa Fe Group sandstone. Middle of unit is composed of yellowish-red (5YR 5/6), moderately sorted, fine-grained (fL) sand with <5% scattered calcium-carbonate nodules. Lower part is light-brown (7.5YR 6/4), fine-grained silty sand.	1.3–2.7
C.	Slightly pebbly sand; very pale brown (10YR 7/4-8/4), poorly sorted, massive, very fine to coarse-grained (vfL-cL) sand. Upper 60–80 cm is hard and contains scattered cylindrical calcium-carbonate nodules and possible stage II carbonate morphology. Texture is similar to unit 3. Lower 2 m composed of light-brown to light-yellowish-brown (7.5YR-10YR 6/4), poorly sorted, massive to medium-bedded, very fine to medium-grained (vfL-mL) slightly pebbly sand with 5–10% scattered subrounded to subangular pebbles. Lower 1 m contains lens of loose pebbly sand that contains slightly more pink and red granite and fewer gray and black volcanic clasts.	2.0–4.8
D.	Sandstone and pebbly sandstone; poorly exposed.	7.0
E.	Sandstone and pebbly sandstone; poorly exposed, 2-cm-thick pumice-bearing pebble conglomerate approximately 3 m above base of unit.	4.5
F.	Pebble conglomerate; pink (5-7.5YR 7/4), thin- to medium-bedded, clast-supported, pebble conglomerate with interbedded thin- to medium-bedded, horizontally stratified sandstone; consolidated, cemented with disseminated calcium carbonate, and forms ledge. Gravel composes about 80–90% of unit. Sandstone is moderately sorted (vfL-vcU; mode is mL). Conglomerate beds generally 30–40 cm thick and are trough cross-stratified. Base is scoured approximately 2–15 cm into underlying sandstone. Basal gravels contain locally abundant vesicular basaltic pebbles. Cross-stratification (n=3) indicates S35E–S60E paleoflow directions.	3.0

Appendix D

Type stratigraphic section of the Santa Ana Mesa Member of the Ceja Formation beneath Santa Ana Mesa, Santa Ana Pueblo quadrangle, Sandoval County, New Mexico (**SAM**, Fig. 11). Measured and described by Paul E. Soister along southwestern margin of Santa Ana Mesa, below lava flows of San Felipe volcanic field. The location of this stratigraphic section is not precisely known, but was probably measured at one of a few well-exposed gullies on the southwestern edge of Santa Ana Mesa. Stratigraphic descriptions are simplified from Soister (1952, table IV, pp. 40–42). The boundary between the Santa Ana Mesa Member and Arroyo Ojito Formation is provisional and was interpreted from unit descriptions and examination of aerial photography and satellite imagery.

Unit	Description	Thickness (m)
Ceja Formation, Santa Ana Mesa Member (Tcs, 237–245 m)		
18.	Sandstone and siltstone, light-pinkish-brown to orange-brown, medium- to thick-bedded; mostly well cemented by calcium carbonate; argillaceous; scattered pebbles and cobbles in some beds.	61–69
17.	Siltstone and sandstone, pinkish-brown to medium-brown; well cemented by calcium carbonate; grains range in size from silt to medium sand and include quartz with minor feldspar, biotite, and muscovite.	18
16.	Sandstone, dark-reddish-brown, thin-bedded, calcareous, ferruginous, argillaceous, conglomeratic; alternate hard and soft beds; sand grains are mainly subangular to subrounded, and sorting is fair to poor.	33
15.	Sandstone, light-brown to medium-brown, medium-bedded, poorly consolidated, calcareous, argillaceous, slightly conglomeratic; mostly subrounded quartz grains.	29
14.	Conglomerate, light- to dark-reddish-brown; coarse particles are granules and pebbles with scattered cobbles including red granite and gneiss, limestone, basalt, quartzite, and weathered tuff; minor 0.3-m-thick sandstone.	22
13.	Sandstone and mudstone; thin, hard layers of calcareous, very fine to fine-grained, well-sorted sandstone alternates with calcareous red clay and with poorly consolidated conglomeratic sandstone.	11
12.	Conglomerate and sandstone, reddish-brown, thin- to medium-bedded, poorly consolidated. Sandstone is calcareous and fine to medium grained.	4
11.	Sandstone, tan to medium-brown with some bleached spots; hard beds cemented by calcium carbonate alternate with poorly consolidated beds; fine to medium grained; argillaceous. Contains a few fragments of tuff and scattered subangular granules that are mainly red granite.	10
10.	Sandstone, medium-brown to reddish-brown, thin- to medium-bedded; alternating consolidated and semiconsolidated conglomeratic sandstone; coarse particles are subrounded granules and pebbles of chalcedony, red granite and gneiss, sandstone, quartzite, and basalt; andesite and rhyolite rock types are absent or rare.	21
9.	Conglomerate, reddish-brown, thin- to medium-bedded; coarse particles, predominantly pebbles, are same as in the overlying unit; contains abundant cobbles and scattered boulders; sand matrix makes up 60% of unit.	5
8.	Sandstone; medium-brown to reddish-brown, thin- to medium-bedded; slightly calcareous, poorly consolidated beds alternate with very calcareous hard beds. Two 0.3-m-thick beds of reddish and medium-brown clay near middle.	7
7.	Sandstone, light-brown to pinkish-brown, medium-bedded; argillaceous; lenses of semiconsolidated sand and silt alternate with beds of hard calcareous sandstone. Many possible fossil tracks, trails, and worm burrows.	10
6.	Sandstone, reddish-brown, conglomeratic; argillaceous. Basal contact with Arroyo Ojito Formation is inferred.	6
Arroyo Ojito Formation(?), probable Loma Barbon Member (52 m)		
5.	Conglomerate; pebbles and scattered cobbles.	1
4.	Siltstone and sandstone; medium-brown, poorly consolidated, fine-grained sandstone with clay lenses.	6
3.	Sandstone, tan to brown, medium- to thick-bedded, poorly consolidated, and argillaceous with minor pebble lenses.	9
2.	Conglomerate and conglomeratic sandstone; contains granules, pebbles, and small cobbles of red granite, white silty limestone, quartzite, and chert.	1
1.	Sandstone with clay lenses; tan to brown with minor gray beds, medium to thick bedded, some crossbedding, poorly consolidated, argillaceous, poorly to well sorted; calcium-carbonate cement in harder beds and clay with some calcium carbonate forms cement for others. Sand grains are very fine to medium-grained, subangular quartz, feldspar, and minor dark minerals. Beds stained by clay. A 0.6-m-thick clay bed near top is dark reddish brown, fairly hard, noncalcareous, and silty. Thin pebble lenses near top; pebbles include limestone, pink and red granite, basalt, chert, and quartzite.	35

Appendix E

Reference section of the Santa Ana Mesa Member of the Ceja Formation, San Felipe Pueblo quadrangle, Sandoval County, New Mexico (**SFP**, Fig. 11). Measured and described by Nathalie Brandes and Sean Connell along southeastern margin of Santa Ana Mesa. Fluvial deposits of the Santa Ana Mesa Member (Ceja Formation) interfinger with axial-fluvial member of the Sierra Ladrones Formation beneath late Pliocene basaltic lava flows. Base of measured section at N: 3,918,355 m, E: 364,800 m. Measured upsection from unit 1 by Nathalie Brandes and Sean Connell on June 16, 2000 (Brandes 2002); modified by Sean Connell in March 2007.

Unit	Description	Thickness (m)
Basaltic lava flows of San Felipe volcanic field (Tb, 3 m)		
18.	Tholeitic basalt, very dark gray (N3/), vesicular; fine- to medium-grained plagioclase laths and olivine crystals are visible in hand specimen; base typically covered by hillslope colluvium; 10–30 cm of coarse-grained basaltic tephra locally exposed.	3.0

Sierra Ladrones Formation, axial-fluvial member (QTsa, 28 m)		
17.	Sandstone, pinkish-gray (5YR 6/2), mL to vcU, moderately sorted, subangular to subrounded with thin silty sandstone bed; upper 1 m contains massive to cross-stratified well-sorted sand, possibly eolian; top is slightly reddened with baked zone at top; unit is very poorly exposed.	3.4
16.	Gravel, pebble and cobble; abundant rounded quartzite and volcanic gravels; clast supported; planar crossbedding. Clasts are 3–12 cm in diameter.	9.3
15.	Mud with sand interbeds, light-red (5YR 5/4); medium to thickly bedded with thin- to medium-bedded sand interbeds constituting about one-quarter of unit.	3.0
14.	Sand and pebbly sand, pinkish-gray (5YR 6/2), fL to cU, moderately sorted, subangular to subrounded, laminated to medium-bedded, cross-stratified; unit is poorly exposed.	11.9
Ceja Formation, Santa Ana Mesa Member (Tcs, 16 m)		
13.	Sandstone with interbedded mud, light-reddish-brown (5YR 6/4), fL to mU, moderately sorted, subangular to rounded; weakly cemented with calcium carbonate; scattered medium-bedded pebbly sandstone lenses present; mudstone interbeds are 2–4 cm thick; upper contact is poorly exposed.	5.2
12.	Silty sand interbedded with mud, light-reddish-brown (5YR 6/4), vfL to fU, well-sorted, subangular to rounded; weakly cemented with calcium carbonate; sandy beds are 13–20 cm thick interbedded with 3–7-cm-thick, red (2.5YR 5/6) mudstone; culminates in a possible buried soil with stage II pedogenic carbonate morphology.	11.0
Sierra Ladrones Formation, axial-fluvial member (QTsa, 32 m)		
11.	Sand and pebbly sand, pinkish-gray (5YR 6/2), mL to vcU, moderately sorted, subangular to subrounded; basal 70 cm cemented with calcium carbonate; laminated to thickly bedded; cross-stratified; unit is poorly exposed; contains lenses of rounded pumice pebbles.	3.9
10.	Sandstone and mudstone, pink (7.5YR 7/3), vfL to fU, well-sorted, subangular to subrounded; cemented with calcium carbonate; planar crossbeds 10–20 cm thick; about 30% of the unit is light-red (2.5YR 6/8) mudstone interbeds approximately 2–4 cm thick.	6.6
9.	Sandstone, pinkish-gray (7.5YR 7/2), mL to vcU, well-sorted, subangular to rounded; base is locally very well cemented with calcium carbonate; distinctly cross-stratified 20–25-cm-thick beds.	11.5
8.	Muddy sandstone, light-brown (7.5YR 6/4), vfL to cL, moderately sorted, subangular to subrounded; medium planar cross-bedded sand, well cemented with calcium carbonate; contains root tubes 1–2 cm long with some as long as 6 cm forming discontinuous rhizoconcretionary mats; minor beds of pebbly sandstone that fine upward into the muddy sandstone.	2.8
7.	Silty sandstone, very pale brown to pink (10YR 8/2 to 7.5YR 7/3), vfL to mL, moderately sorted, subangular to subrounded; well cemented with calcium carbonate; locally abundant rhizoconcretions as much as 15 mm in diameter.	1.9
6.	Sands with gravel lenses, light-gray (10YR 7/2), mL to vcL, moderately sorted, subangular to subrounded; cross-stratified in beds 20–30 cm thick; gravel lenses are medium planar bedded containing abundant rounded quartzite and porphyritic tuff.	5.5
Ceja Formation, Santa Ana Mesa Member (Tcs, 27 m)		
5.	Silty sand with mud interbeds, yellowish-red (5YR 5/6), vfL to cU, moderately sorted, subangular to subrounded; occurs in 15–50-cm-thick planar to cross-laminated silty sand interbedded with 10–20-cm-thick, reddish-yellow (5YR 6/6) mud.	7.7
4.	Conglomerate, pebble- to cobble-sized, subangular to subrounded; granite, volcanic tuff, and rare Pedernal chert; clast supported; poorly sorted; crude planar bedding; grades finer upsection into a red to yellowish-red (2.5YR 5/6 to 5YR 5/6) sandstone, fL to cU, moderately to poorly sorted and exhibiting faint low-angle cross-stratification.	4.7
3r.	Sand, light-brown (7.5YR 6/4), fL to mU, moderately sorted, subangular to subrounded; bedding indistinct; poorly exposed unit; possibly a lens of axial-fluvial deposits of Sierra Ladrones Formation.	1.0
3.	Sand, light-reddish-brown (5YR 6/4), fL to cU, moderately sorted, subangular to subrounded, laminated to thinly bedded; planar to low-angle cross-stratification; rare pebbly sandstone interbeds. Scattered 30–40-cm-thick, clast-supported, pebble- to cobble-sized gravel lenses with granite and volcanic clasts present. Unit is poorly exposed.	9.5
2.	Silty sand, reddish-yellow (5YR 6/6), vfL to vcL, poorly sorted, subangular to subrounded; thin planar bedding. Locally abundant 3–8-cm diameter concretions and rhizoconcretionary beds. A single 3–6-cm-thick mud bed exhibits square to polygonal mud cracks.	2.6
1.	Sandstone, reddish-yellow (5YR 6/6), vfL to mU, moderately sorted, subangular to subrounded; thin planar beds; contains discontinuous thinly bedded pebbly sand. Top of unit is marked by 30-cm-thick well-cemented rhizoconcretionary root mat.	1.0
Sierra Ladrones Formation, axial-fluvial member (QTsa, >0.2 m)		
0.	Sand, light-brown (7.5YR 6/4), fL to mU, moderately sorted, subangular to subrounded; bedding indistinct; poorly exposed unit; probably axial-fluvial deposits of the Sierra Ladrones Formation. Base is not exposed.	0.2